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A Method for Use Phase Definition as Integrated into an Object-Oriented Approach to Life Cycle Assessment

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A Method for Use Phase Definition as Integrated into an Object-Oriented Approach to Life Cycle Assessment

by

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M.S. Degree Thesis

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Abstract

As global environmental concerns increase, industries continue to respond prominently to meeting sustainable practice standards through technological innovations and new business models. However, current sustainability measurement tools, including Life Cycle Assessment (LCA), do not provide practitioners with sufficiently standardized methodology, which leads to uncertainty and limited comparability of results. This research develops a systematic Object-Oriented LCA method to define and quantify the consumed life of a product system during the use scenario under analysis. In this method, the Cumulative Damage Function (CDF) quantifies the consumed life of a product by using inputs of total efficiency or damage, scaling parameters and a use scenario. By adding a systematic methodology around use parameter, scaling parameter, damage multiplier, and energy definition there can be confidence that the framework's CDF accurately represents the product system use phase. In particular, the new contribution of a damage multiplier creates a model that quantifies the unique aspects of user behavior that are otherwise not captured by product engineering metrics. The proposed method was applied to a practical case study to assess the effectiveness of the approach and the feasibility of modeling using SimaPro® software. The results demonstrate that a systematic approach using common tools, such as functional decomposition, to define use phase parameters helps remove practitioner variability and increase accuracy of quantifying a product system use phase.

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1. Introduction

Every day companies manufacture and distribute products while customers use and dispose of products. Companies should consider the environmental impacts throughout the manufacturing, distribution, use and disposal of a product to minimize negative environmental impacts. There are many different environmental assessment tools to consider product environmental impacts including risk assessment, environmental performance evaluation, environmental auditing, and environmental impact assessment. Most of which implement measurements in terms of relative ratings that results in shifting of burdens ("ISO 14040," 2006). This is referred to as the “less is better” approach by which a product system that causes less environmental impact is rated more positive than an alternative with the same function (Owens, 1997). A Life Cycle Assessment (LCA) on the other hand, is the only tool which uses quantitatively deterministic measurements to convey results (Klöpffer, 1997). Even from the start of LCA methodological development around 1970 it was clear that there are many benefits of conducting this type of environmental assessment over others.

From 1990 to 1993 SETAC (Society of Environmental Toxicology and Chemistry) and SETAC-Europe developed a “code of practice” as the first effort to regulate the method of conducting an LCA. This code distinguished four components including goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and life cycle improvement assessment (Rebitzer et al., 2004). The overall intent of carrying out an LCA is to determine the environmental impacts associated with a product system from ‘cradle to grave’, which includes everything from raw material extraction, energy acquisition, material production, manufacturing, use, recycling, and the ultimate disposal ("ISO 14040," 2006; Klöpffer, 1997; Rebitzer et al., 2004). This ‘cradle to grave’ approach is a big part of what makes the LCA tool irreplaceable, because when taking the entire life cycle into account the problem of shifting environmental impacts to unaddressed life cycle stages is avoided (Finnveden, 2000).

Another commonly recognized advantage of conducting an LCA is that it is the only tool that allows for the comparability of environmental consequences that arise from two different products (Finnveden, 2000). Assessment results could also be used for system optimization, benchmarking, integrated into the product design phase, product system improvements, or to identify trade-offs in materials, energy, and releases (Finnveden, 2000; Klöpffer, 1997; Owens, 1997). While initial LCA studies were mostly concerned with comparing product packaging, studies have now been applied to numerous systems for many different purposes (Klöpffer, 1997). LCAs can be applied to the needs of various stakeholders including government organizations, non-governmental organizations, public policy makers, private industry sectors, and essentially any other type of decision maker (Finnveden, 2000; Rebitzer et al., 2004).

As the LCA tool became more widely used through the twentieth century it quickly became evident that analysts would produce different and sometimes conflicting results for the same system depending on the methodological choices (Russell, Ekvall, & Baumann, 2005). These discrepancies highlighted the need for a more rigid LCA standardization framework. Based off of the SETAC "code of practice" the International Organization for Standards (ISO) created the 14040 framework, which outlines the main principles of an LCA for practitioners to use. Later, the ISO created the 14041 framework, which details the requirements and guidelines to conduct a more accurate LCA (Klöpffer, 1997). Ultimately the goal was, and continues to be, the establishment of a set of stringent requirements that help practitioners to develop the most accurate presentation, assessment, and interpretation of LCA results (Cooper, 2003). This move towards standardized LCA implementation requirements serves as the motivation for this research.

2. Background

2.1. ISO Framework

There are four defined phases in the ISO 14040 LCA standard which includes the goal and scope definition, inventory analysis (LCI), impact assessment (LCIA), and interpretation ("ISO 14040," 2006) (see **Error! Reference source not found.**). The goal and scope phase describes the product system in terms of system boundaries, a functional unit, reference flows, and defines the necessary assumptions and methods used in later phases (Klöpffer, 1997; Reap et al., 2008a; Rebitzer et al., 2004). A functional unit is defined by the ISO as "…a measure of the performance of the functional outputs of the product system" and its purpose is "to provide a reference to which the inputs and outputs are related…[and]…to ensure comparability of LCA results". The reference flows are then defined as the amount of product necessary to complete the assessment per functional unit including the type and quantity of materials and number of material replacements during the analysis lifetime (Cooper, 2003; Frijia et al., 2012). When completing the goal and scope phase the most important factors to consider are the systems unit processes, life cycle stages, impacted geographical area, and the relevant time horizon (Reap et al., 2008a).

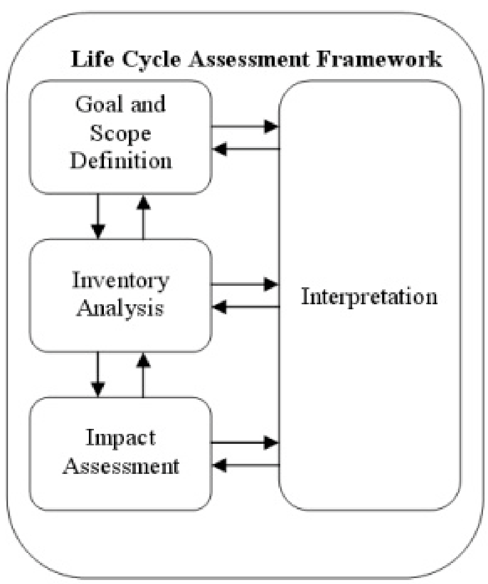

Figure 1: ISO 14040 Phases for Completing an LCA

The thorough definition of the goal and scope phase is critical in order to carry out a comprehensive assessment and to best identify the impact areas the assessment focuses on (Bousquin, et al., 2012). The following section will discuss in greater detail why this first phase of conducting an LCA is so vital to the entire assessment. More specifically, how the choices and assumptions that the practitioner makes with respect to the goal and scope phase influence the accuracy, comparability, and credibility of the LCA results (Rebitzer et al., 2004).

The second phase of an LCA is the inventory analysis, which is the compilation, tabulation, and preliminary analysis of all environmental exchanges associated with the product system in study (Rebitzer et al., 2004). This phase is the central data component of the whole assessment and it is the most developed of the four phases (Klöpffer, 1997). Once the flows of material and energy into, though, and out of the product system are defined and quantified using the most relevant data sources, the practitioner can proceed to the impact assessment phase (Reap et al., 2008a). While a study could culminate after the LCI is complete, the results are only useful for a comparative assessment when the full impact assessment is done. LCI results on their own provide useful information for product improvements, benchmarking, energy savings, and emission reduction (Klöpffer, 1997).

During the impact assessment phase the inventory data is converted into environmental impact estimates using a process of classification, characterization, normalization, and weighting (Klöpffer, 1997; Reap et al., 2008b). These impact estimates are associated with different classes of environmental issues, known as impact categories. For each of these categories a life cycle impact category indicator is selected and the results are calculated in terms of these selected indicators ("ISO 14040," 2006). Many different impact categories have been created, some more commonly used than others, but only the categories with indicators of Global Warming Potential (GWP) and Ozone Depletion (ODP) have international consensus on their use and validity (Klöpffer, 1997).

The fourth phase of an LCA is known as the Interpretation phase; however this process usually occurs throughout the assessment ("ISO 14040," 2006; Reap et al., 2008b; Rebitzer et al., 2004). Based on inventory and impact assessment data the interpretation aims to formulate a critical evaluation of the whole LCA, link the LCA with external applications and formulate recommendations for the stakeholders (Klöpffer, 1997; Reap et al., 2008b). The total effect of a product systems impacts on the environment is a function of a limitless number of variables including location, medium, time, rate of release, route of exposure, natural environmental process mechanisms, distribution in environmental media, etc. (Owens, 1997). Overall, interpretation aims to emphasize the strengths and limits of an LCA study in relation to the goal and scope definition. In addition, the interpretation should not bias the fact that LCA results are based on a relative approach that indicate potential environmental effects and do not predict actual impacts ("ISO 14040," 2006).

The ISO 14040 framework explicitly states that “it does not describe the LCA technique in detail, nor does it specify methodologies for the individual phases of the LCA”; rather its purpose is to describe the essential principles and general guidelines (1). There is no single way to conduct an LCA as long as the methods are in accordance with the ISO framework, the intended application as defined in the goal and scope phase, and the requirements of the practitioners’ organization then the study will be generally accepted. However, it is detailed that specific requirements must be applied to an LCA study when it is intended to be used as a comparison disclosed to the public ("ISO 14040," 2006). The ISO is continually recognizing the need for greater standardization in the LCA methodology in order to increase study acceptance and compatibility, but the actual execution of this standardization has not yet been seen for the goal and scope phase (Finnveden, 2000; Rebitzer et al., 2004).

2.2. Importance of the Goal and Scope Phase

Thoroughly completing the goal and scope phase is imperative to an LCA study because of the implications this phase has on the rest of the study. During the goal and scope phase, the functional unit defines what is being studied so that all inputs and outputs in the LCI, and subsequently the entire LCIA, are related to a common unit of measure. Owens 1997 goes as far as to state that the functional unit is the LCA mathematical “inventory accounting measurement of efficiency”. This unit reference is also necessary to ensure that results are comparable to other product systems with the same function or other LCA studies (Bousquin et al., 2012; "ISO 14040," 2006; Judl et al., 2012). Along the same lines, the definition of the system boundaries must be based on the most repeatable, objective, and scientific based information possible because otherwise they may not reflect reality well enough to lead to admissible results and interpretations

(Reap et al., 2008a; Rebitzer et al., 2004). The definition of the system boundaries is highly dependent on the context of the study and the assumptions of the practitioner (Bousquin et al., 2012). Since the boundary definition is not a standardized process it is an application-dependent methodology contingent on the environmental, economic, or social consequences of the decisions and position of the decision makers and study stakeholders (Wenzel, 1998). The goal and scope phase as a whole is essential as it effects each of the subsequent phases including the raw data standardization, identification of the impact areas of focus, and the credibility and confidence of the results (Bousquin et al., 2012; Owens, 1997; Reap et al., 2008a).

Rebitzer et al. (2004) point out that throughout the ISO 14040 framework, statements such as "…depending on the goal and scope of the LCA" are used without any thorough description of how to define the goal and scope or how it should ultimately affect the assessment (703,705,709, 714). The ISO 14040 standard states the "the depth and the breadth of LCA can differ considerably depending on the goal [and scope] of a particular LCA", which specifically highlights how important the comprehensive and standardized definition of this phase is to conducting an accurate LCA (V). Given how involved a full LCA study is in addition to how critical the goal and scope definition is, the thorough, well-justified, and transparent definition of the study context, functional unit, and system boundaries can easily add credibility and confidence to the results. While some argue that a more involved goal and scope definition would require more data and time with little value added, the implementation of standardized methodology could add significant value to the assessment while not requiring much more added expenses (Reap et al., 2008a).

2.3. Constraints of Current Goal and Scope Phase Definition

Methodological standardization is specifically needed for the initial phase of an LCA because of the impact that the functional unit definition has on the entire assessment. When establishing the study context and system boundaries, it is important to consider that the scale of inclusion will directly affect how the product system function is defined. If too narrow of a perspective is taken there will be variation in the function of a product system as compared to its alternatives (Rebitzer et al., 2004). Expanding system boundaries can help ensure consistent function definition of alternative product systems, but this also drastically increases the need for data and increases the opportunity for misguided results (Reap et al., 2008a; Rebitzer et al., 2004).

Once again, the ISO 14040 framework remains vague and subjective on this matter by simply stating that the selection of a system function is dependent on the goals and scope of the study instead of outlining a reliable method (Cooper, 2003; Hischier & Reichart, 2003; "ISO 14040," 2006). Once a function is assigned to the product system, the methodological concerns continue, as the function must be quantifiable in a reliable and scientifically measurable way in terms of the functional unit and reference flows (Hischier & Reichart, 2003).

In many LCA studies there are complications surrounding the definition of the functional unit and its associated reference flows. As a result, functional units tend to be over simplified or insufficient in a way that only the main system function is captured and the parameters do not represent all of the system effects (Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2010; Finkbeiner et al., 1997). While following the current LCA methodology framework, there are often many different functional units a practitioner can choose from, all of which are correct. However, different functional units for the same product system lead to different and possibly incorrect results (Finkbeiner et al., 1997; Hischier & Reichart, 2003; Reap et al., 2008a). If an assessment is vague in its functional unit definition or if there are noted issues, the confidence in the final LCA results significantly decrease (Reap et al., 2008a). Due to the documented inconsistencies surrounding functional unit definition, the resulting concentrations of emissions and other environmental impacts are only potential or hypothetical effects (Klöpffer, 1997).

The most notable sources of functional unit complication or error include:

- Missed or wrongly specified or prioritized system functions
- Over broadening and simplifying the functional unit
- Narrowing the functional unit such that it does not capture the entire system
- Assigning functional units to non-quantifiable or difficult-to-quantify functions
- Inconsistent methods of dealing with multi-function product systems
- Uncertainty in product use scenarios and system dependencies
- Making strict, functionally-equivalent system components

Many product systems have functions or components to them that are non-quantifiable or difficult-to-quantify, but are still important to the product systems life cycle. Some of these functions include aesthetics, entertainment, or learning. These functions often lead to the use of proxies or subjective units or measure to define the functional unit and therefore cause a lack of confidence in the LCA results (Reap et al., 2008a).

Another source of error comes from assessing products that have multiple functions. If a narrow or limited-in-scope functional unit is used on a multi-functional product system then relevant environmental impacts will most likely not be captured in the results. However, if the reference unit is too broad it creates the need for more assumptions and once again will most likely not appropriately capture the environmental impacts in the results (Bousquin et al., 2012; Hischier & Reichart, 2003). Consequently the practitioner should identify, decompose, specify, and/or prioritize the various functions appropriately with respect to the study so that the functional unit reflects reality as accurately as possible (Reap et al., 2008a). Even with the use of a logical methodology, functional unit definition remains complicated in a multifunction system because of the need for an assumption laden goal and scope phase and because of the various outputs that the single product can produce (Bousquin et al., 2012). There is a great deal of criticism surrounding the amount of subjectivity that the ISO standards allow, which leads to inaccurate functional unit definition and little confidence in LCA results.

The use phase of a product's life cycle is especially biased towards the practitioner's assumptions because the use of many products cannot be well generalized to fit all consumer patterns. When the use scenario and external system dependencies are not certain, functional unit definition remains ambiguous, as the practitioner must assume what scenario best reflects reality. If a functional unit is defined in a very ridged manner based on generalized life cycle assumptions there is a greater chance for error throughout the LCA because there is no scientific standardized reasoning behind the methodology (Reap et al., 2008a). These general assumptions also lead to potentially inaccurate comparative life cycle product system assessments. In many cases it cannot be definitively determined if one product is environmentally preferable over another product because results and conclusions are not consistently produced (Finnveden, 2000). While this lack of consistency in results stemming from variable functional unit definition is the main contributor to lower confidence in comparative LCA studies, it is also difficult to objectively decide which product system is better because results dependent on the impact category prioritization (Klöpffer, 1997; Rebitzer et al., 2004). Misallocation of environmental burdens is also a largely cited source of incomparability between LCA results (Reap et al., 2008b), but will not be addressed in this study as it is outside of the goal and scope context.

Overall, the lack of structure in functional unit definition during the goal and scope phase is a critical gap in LCA methodology. If this issue is solved, most all of the discussed limitations will be resolved and confidence in LCA results will increase significantly (Cooper, 2003; Klöpffer, 1997; Reap et al., 2008a)

2.4. Current State of Functional Unit Definition and Standardization

With the widely recognized lack of structure in LCA methodology put forth by the ISO standards, multiple studies have developed and tested methods that attempt to standardize functional unit definition in the goal and scope phase (Finkbeiner et al., 1997; Frijia et al., 2012; Judl et al., 2012; Kwak et al., 2012; Ruhland et al., 2000). A comprehensive review of the attempts to standardized functional unit definition can be found in Fumgalli (2012) and Esterman et al. (2012). In those same works, a framework for what would ultimately become an Objected-Oriented approach for LCA was developed (Fumgalli 2012; Esterman et al., 2012). In this section, the framework developed by Fumagalli (2012) will be critically reviewed. This will be followed by a review of works that support this approach, as well as a summary of the state of the art in functional unit definition. This section will close with a review of the role of LCA in product development. Ultimately, the literature presented in this section reaffirms that while there has been attention given to developing a more reliable functional unit methodology, no current method has sufficiently achieved this goal.

2.4.1. Dynamic LCA Framework

Many of the shortcomings that are identified above in the LCA goal and scope phase definition can be resolved with the implementation of an object-oriented LCA methodology. The starting point for this framework is derived from the Dynamic LCA methodology works of Fumagalli (2012) and Esterman et al. (2012). The Dynamic LCA Framework used systems engineering principles and functional analysis to develop three propositions and define four implementation steps. Figure 2 shows how each of the three propositions are implanted through methodology steps.

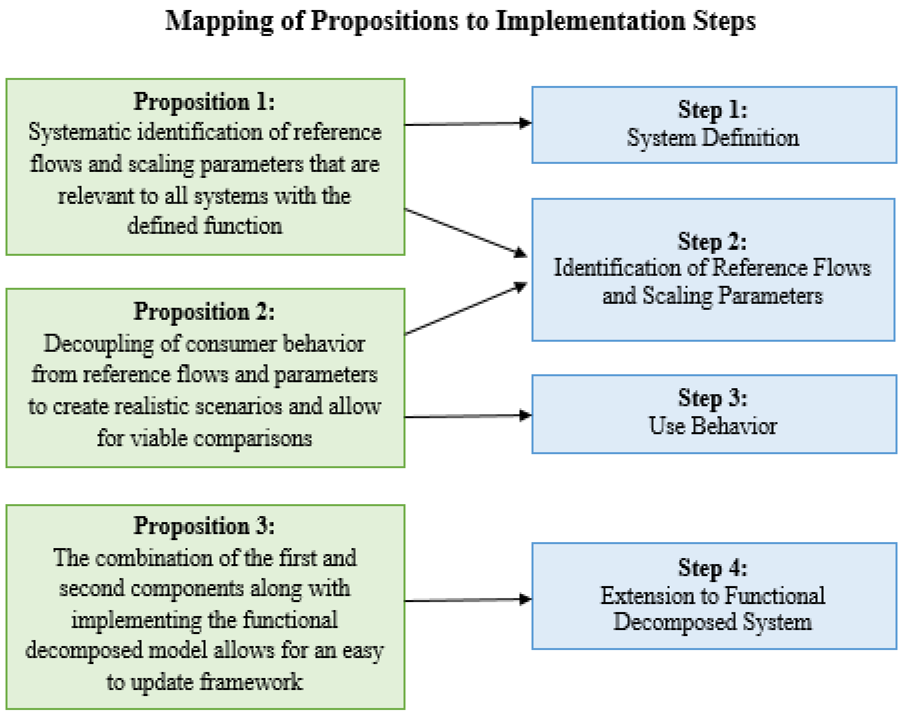

Figure 2: Visual Representation of How Each Framework Proposition is Implemented through a Methodology Step

The first proposition rigorously defines the enclosing system of interest by defining system inputs and outputs so that LCA reference flows and scaling parameters can be systematically identified. It should be noted that this process of defining boundaries related to the use phase (as opposed to the system boundaries of the entire LCA). This process is of great importance because the failure to fully understand and define what flows are linked to product usage could lead to a limited object-oriented model and an increase the difficulty of implementing the framework.

The second proposition decouples consumer behavior from the defined LCA reference flows and scaling parameters so that accurate and complete use scenarios can be constructed. This allows comparison of LCA results between product systems that may use radically different technologies while still fulfilling the same function.

The third proposition leverages the first two propositions to suggest that a functionally decomposed model allows for an object-oriented approach where the modeling techniques of proposition 1 and 2 are recursively applied to the functionally decomposed model. This leads to an approach that is dynamic in nature and easy to update as data quality improves.

Fumagalli's (2012) research highlighted the importance of the first two propositions to ensure that everything that is common to every product in that system class has been set up so that the appropriate parameters to build complete use scenarios can be defined and derived. The three propositions are implemented in a cohesive four-step framework in: System definition, Identification of use and scaling parameters, Use behavior, and replication of these steps on a functional decomposed system. It should be noted that this last step was the subject of work by Gadre (2016) and Deo (2016), while the focus of this work is on the use-behavior.

Step 1 – System Definition

In both LCA work and Systems Engineering, establishing the system boundaries is a well-established principle. According to the ISO 14040 framework, "The system boundary defines the unit processes to be included in the system." LCA system boundaries are based on physical aspects of the system including manufacturing processes (12). In comparison, Systems Engineering defines system boundaries in a more abstract manner.

This framework adapts a model of system boundary definition from Hull et al. (2005) in which system functionality is used instead of the traditional use of physical systems or manufacturing processes (Reference error). While the systems engineering approach is important to consider in this framework based off of well-established systems concepts, the boundaries are not the same as those defined by an LCA. The 'Enclosing System' boundaries shown in Figure 3 represent the life cycle use phase boundaries, which is an integral part of the larger LCA study system boundaries also shown in Figure 3. It is critical to the object-oriented framework that the use phase boundaries and the corresponding parameters are well defined. It is worth emphasizing that the flows that are identified within the enclosing system do represent all flows, but only the flows that are common to **all** systems in that class.

By systematically defining the system of interest use phase boundaries the LCA will be constrained so that the use and parameters can be scaled to use behavior scenarios. This is the essence of what makes this framework dynamic; enabling comparability and use phase updating of the system analysis without reproducing the entire life cycle inventory

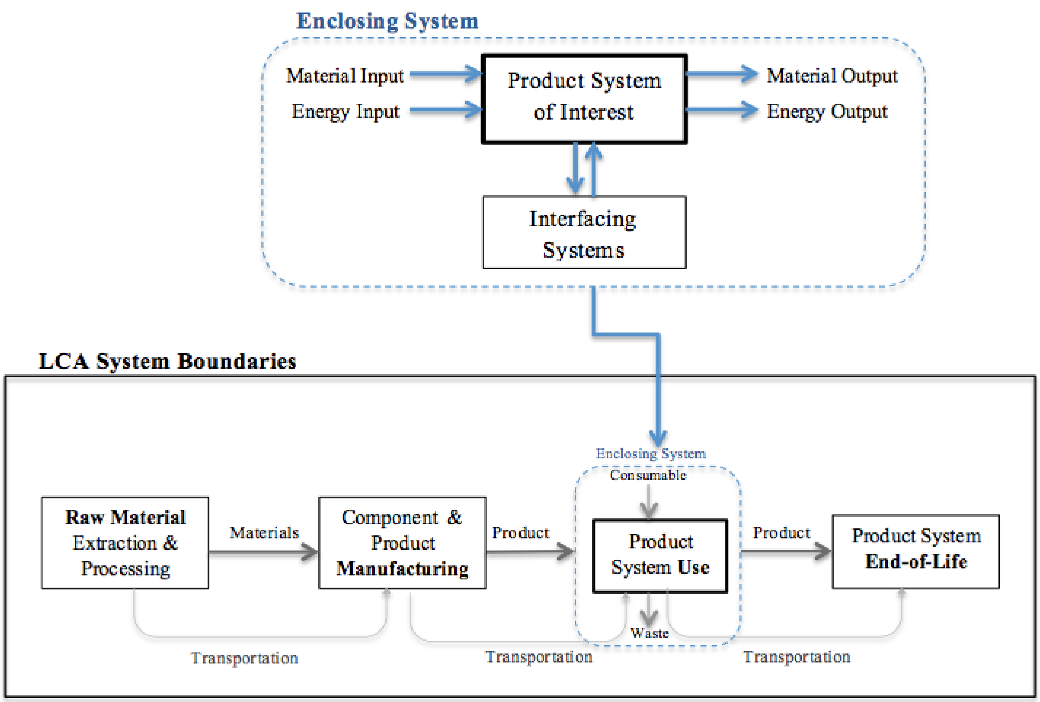

Figure 3: Detailed Use Phase Boundaries within LCA Boundaries Context

The product system of interest as labeled in Figure 3 is described by standard functional analysis as an active verb-noun pair. The verb describes the principal function of the system and the noun describes the object flow involved in the defined function (R. Stone & Wood, 2000). The function must remain at a high level of abstract as to ensure that it is solution independent and can consider a wide range of scenarios. The three flows considered in functional analysis applications are energy, material and information. In the case of an environmental impact assessment the information flow is not relevant in the sense that it is typically encoded with an energy signal and displayed using material resources so it can be accounted for with these two flows. Within the initial framework proposed by Fumagalli (2012) there were no guidelines on how to define the use phase system inputs and outputs. However, this the work will consider this limitation in standardization.

A critical part of this first framework step is to establish the system material and energy transformations because these are what help to define the use and scaling parameters for the established class of systems. While a previous function unit standardization attempt suggests defining every possible scaling parameter based on all applications (Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2010) that is not necessary in this object-oriented LCA framework because of the unique system boundary definition. As stated previously, this framework considers the common flows to all systems of interest.

The final features to this first framework step of system definition are to identify the enclosing system and the interfacing systems. Defining the enclosing system (e.g. Earth's gravitational field) establishes the context of the system of interest. The context is further refined when the interfacing systems (e.g. transportation system) common to all systems of interest are defined.

Step 2 – Identification of Use and Scaling Parameters

After the system boundaries have been defined through the process defined in Step 1, the system relevant use and scaling parameters must be identified. The use parameters are inherent to the system thus the system and boundary definition will help to identify them. The parameters must be in terms of the system use phase input or output flows and must correlate to ultimate system impacts in order to enable object-oriented modeling. It is important that the practitioner keeps in mind two aspects when completing this step, first that the relevant parameters must be abstract enough to remain technology and solution independent. Second, the parameters must be ultimately scalable by consumer use patterns. If these considerations are neglected the object-oriented modeling of the system during assessment will be highly constrained if not impossible.

Step 3 – Use Behavior

Use behavior is important to identify for the accuracy of a life cycle assessment because it reflects the end-user impacts. However, when use behavior is integrated into the functional unit definition the comparability of LCA study results becomes limited. Fumagalli (2012) points out that "by decoupling use patterns from the functional unit definition, a more structured inventory and impact analysis can be conducted in terms of the reference flows and scaling parameters…" (41). The dynamic and object-oriented aspects of this LCA framework is contingent upon the ability of the defined use and scalable parameters to be changed based on different use scenarios. Direct and indirect scaling should be considered. Direct scaling refers to the case when the life cycle inventory (LCI) can be scaled as a direct function of the defined use scenario parameters. In comparison, indirect scaling requires the flows to be allocated in proportion to the product unit of interest as a function of the use scenario parameters. In order to systematically account for this scaling this framework defines a "Cumulative Damage Function", which considers that as a function of the system usage parameters, a certain measure of the unit 'life' will be consumed.

Equation 1

$$Allocation\ (\%) = \frac{consumed\ life}{limit\ (L_F, L_{OBS}, L_{NEED})}$$

Where:

Allocation % = gives the total % of the bill of materials to be quantified in the LCI
Consumed Life = represents the use scenario under analysis
L_F = the limit due to failure
L_{OBS} = the limit due to obsolescence
L_{NEED} = the limit due to the lack of need of the product under analysis

The input variables of the Cumulative Damage Function as outlined in Equation 1 are the use parameters. It is important to reiterate that these usage parameters are consistent for all systems that provide the same function regardless of technology. The limit of the product system life is contingent upon the functional limit of the system, the market obsolesce of the class of systems, and the actual system end-of-life disposal. The Cumulative Damage Function specifically defines the equation numerator of 'consumed life' and is a function of the defined use parameters. Overall, the output of the function indicates how much of the product's bill of materials is quantified and allocated in the impact assessment phase.

The dynamic and object-oriented aspect of this framework is permissible through the representation of different use scenarios, which enables the creation of workflows. It is critical to the assessment that these workflows represent equivalent tasks completed by the alternative technologies of interest instead of equivalent "operating regimes", which are technology dependent. While the current state of this framework can accommodate the assessment of different workflows that represent equivalent tasks, there are no guidelines for ensuring this equivalency.

Step 4 –Extension to Functional Decomposed System

Continuing along the same level of abstraction introduced in this framework the functionality of the product can be further decomposed into sub-functions. The first three steps of this framework can then be applied to these sub-functions. Functional modeling is a well-established tool used to decompose the functionality of a product and understand the system in a manner independent of the physical product structure (R. Stone & Wood, 2000). Building off of the initial Dynamic LCA Framework, Gadre (2016) and Deo (2016) re-established the framework title as 'object-oriented' to better align with the purpose of the framework. Gadre (2016) then demonstrated through case study application that when an object-oriented LCA framework is applied to product sub-functions it successfully creates foundational blocks of the environmental impact assessment. Further demonstration of the successful implementation of an object-oriented LCA framework is in Deo's (2016) work, which develops and implements a framework for quantifying the Cumulative Damage Function using concepts from Remaining Useful Life (RUL), reliability analysis and failure analysis.

2.4.2. Literature Support of an Object-Oriented LCA Framework and Current State of Functional Unit Definition

As described, the proposed object-oriented LCA methodological approach to goal and scope phase characterization and specifically the functional unit definition has a framework of three main propositions. These include:

1. Systematic identification of use and scaling parameters that are relevant to all systems with the defined function
2. Decoupling of consumer behavior from use and scaling parameters to create realistic scenarios and allow for viable comparisons
3. The combination of the first and second components along with implementing the functional decomposed model allows for an easy to update framework as data quality improves

Each of the propositions have been used individually or as two concepts together in LCA studies in an attempt to create a more methodologically standardized functional unit definition, however all three have never been implemented into a coherent framework. The integration of this framework uses an object-oriented LCA model, which allows for the manipulation and subsequent updating of the model over time. Additionally, dynamic modeling has been cited to improve the spatial variation and local environmental uniqueness problems often seen in LCA studies (Reap et al., 2008). The multiple LCA studies presented here reinforce the propositions of the proposed framework and act as evidence that these individual concepts are justified and useful in their application to functional unit definition to increase confidence in results and comparability. In addition, the literature presented here reaffirms that while there has been attention given to developing a more reliable functional unit methodology, no current method has sufficiently achieved this goal.

Kwak et al. (2012) conducted a comparative life cycle assessment of complex heavy duty off road equipment in an attempt to offer an objective means of comparing different product systems. In essence, this study implements the first framework component in order to more accurately capture and compare the product systems during assessment. The practitioners define the common function of the two systems as “to lift and move heavy materials around the worksite”, but do not implement any sort of methodical functional analysis. The function definition merely maintains a relatively high level of abstraction in order to ensure all aspects of the systems are captured.

The difficulty in their assessment arises during the functional unit definition because the two products have different levels of productivity, which results in different aging of the machines and therefore varying lifespans of use. Traditionally with heavy machinery the functional unit would be defined as the same amount of operation hours, but since that unit would not accurately capture the comparison of the systems of interest Kwak et al. (2012) implement seven steps to define the functional unit as the same amount of total production. Ultimately, the functional unit reflects that one machine conducts the same amount of work with less power in a shorter amount of time so that it has longer lifetime expectancy. For the machine with a longer lifespan, only a fraction of the total lifecycle is accounted in order to conduct an equal comparison.

While the system is well defined through this method so that the use and scaling parameters are systematically identified to reflect reality accurately, consumer behavior remains integrated into the functional unit definition in a fixed manner so that there is no room for object-oriented modeling of the use phase. The results of this study support the knowledge that environmental impacts vary based on different customer use patterns and usage differs widely from customer to customer (Kwak et al., 2012). While Kwak et al. (2012) state that “Future work will examine how the benefit of each machine changes if the machine is used differently”, this would not be necessary if the framework proposed in this work would have been initially implemented to allow for object-oriented modeling within the life cycle assessment.

Another integral part of the first framework component is the identification of the appropriate use and scaling parameters that are specific to a particular system’s functionality. In the LCA case study by Matheys et al. (2007) they identify the most appropriate functional units for the assessment of different electric and hybrid vehicle batteries and determine the influence of functional unit choice on the results. While this study lacked a thorough definition of the system the practitioners did carefully identify the different parameters related to an appropriate functional basis.

This study illustrates the critical importance of ensuring that the use and parameters are abstract enough to remain independent of technology-based solutions. In choosing an appropriate functional unit Matheys et al. (2007) needed to characterize the defined parameters based on if they were "equal for all technologies" or not. This required the inclusion of parameters and the functional unit definition to be based mostly on "practical significance" instead of system functionality.

Additionally, by defining system parameters as technology dependent the functional unit definition became much more complicated and was most often resolved in literature by oversimplifying the reference basis. Ultimately, this limitation most likely hindered the accuracy of defining functional units so that they didn't truly represented reality well enough to carry out the goal of the study. The methodology in Matheys et al. (2007) is an example of the possible issues of not properly implementing the first proposition of the object-oriented LCA framework. While a relatively unsuccessful attempt was made at formalizing the functional unit definition it is still important to point out that the practitioners of this study readily site the flaws in ISO functional unit definition standardization especially in a product comparison assessment (Matheys et al., 2007).

The comparability of LCAs is limited because the functional unit and system boundaries are often defined based on generalized and fixed consumer use patterns. The lifespan of a product system is directly related to the time in use, rate of wearing, and opportunity for repair, among many other variables. Frijia et al. (2012) conducted a life cycle energy assessment of a building system in order to propose and develop three aspects of LCA methodology including functional unit definition, incorporating technological progress, and parameterization. All three of these aspects that are targeted specifically for the building system are elements of the proposed object-oriented LCA framework. By looking at the success of these elements in this specific case study the framework proposed in this work can be refined and implemented with greater confidence.

Most previous LCA studies of energy in building systems take the operational phase to include all energy use within the residence, which would require a functional unit that captures all household activities. However, these studies exclude related customer supply chains such as food production, appliances, and household chemicals. The second framework proposition is implemented in this case study as it decouples customer behavior from the function which allows for a more complete definition of scaling parameters and functions. While Frijia et al. (2012) points out the need for "the functional unit and boundaries for reference flows be chosen in a consistent way", there is no guidance provided for removing the variable of customer behavior.

The high-level function defined in their study is climate-controlled space, which focuses on the building rather than activities in the building. Associated functional parameters are categorized as structural, electrical, and/or plumbing components of the system and depending on the purpose or scope of the study a functional unit can be defined to encompass the appropriate functions not the operational phase. Results show that using the functional unit decoupled from customer behavior yields a higher contribution from materials and manufacturing which more accurately represents reality. This is because when using a functional unit based off the operational phase the system boundaries were broader and many important supply chains were excluded, thus causing a skewed perspective of minimalized materials manufacturing impacts. The study practitioners recognize that while this study only uses an oversimplified parameter model the implementation of more detailed LCA parameter modeling would allow for object-oriented assessments customized to a user's product supply chain, design and operation characteristics of interest (Frijia et al., 2012).

The LCA methodology that most closely reflects the third proposition of the framework proposed in this thesis is seen in Ruhland, et al. (2000). The systems function was defined along with its associated input output flows of material and energy. By defining the functional relationships between system flows and interacting systems this study considers the function of metal cleaning processes much more thoroughly than any previously cited studies. The functional unit was defined as the reference load of metal cleaning process, which is a function of the load volume and number of loads instead of being a fixed unit. Furthermore, the practitioners used an empirical process model to quantify the relationship between the functional unit, system parameters, and the mass and energy flows. The individual functional parameters in this model depend on the machine type and the technology so for each machine use a new set of coefficients must be determined.

Similar to the object-oriented LCA framework, this study enables the parameters to be scaled based on a specific scenario to define a functional unit for assessment. Unlike the traditionally used LCA approach this empirical model and the proposed object-oriented framework enable a practitioner to consider different uses by appropriately scaling the parameters and allocating them to a functional unit. Additionally, Ruhland et al. (2000) consider the fact that machines do not all operate equally and so scaled the machines to be equivalent assuming a linear relationship between load volume and material and energy flows. While the methodology steps implemented in this case study are object-oriented in nature, it is limited in its specific applicability to equivalent machining technologies (Ruhland et al., 2000). Comparability between LCA studies is greater when the modeling remains technology independent and system functionality based.

It is important to note that while the work of Reap et al. (2008a, 2008b) have been cited over four hundred times in literature, the case studies presented in this section have only been cited a few times each. This indicates that the issue of LCA standardization is well known, but the forward progress towards actually standardizing assessments is limited.

2.5. Current Use of LCA in Product Design and Development

The application of LCAs to product design is of particular interest to many manufacturing companies because by implementing sustainable practices, companies can create a competitive advantage and ultimately drive profitability in addition to mitigating environmental impacts. In order to do so, a number of environmental design tools have been developed, largely categorized as design for the environment (DFE). While there is a common consensus in industry that environmental product development is a key issue that needs to be implemented in the early stages of a product's life cycle, most methods are extremely complex to understand and implement, especially at the early design stage (Chang et al., 2014; Chiu & Chu, 2012). Most all DFE methods integrate life cycle assessment in order to ensure that the product system is fully captured and there is no shifting of burdens between life cycle phases (Finnveden, 2000). However, the use of full LCAs is a major contributor to the complexity of DFE methods because LCAs require a large amount of data, time, and cost input in addition to often producing conflicting results (Chen & Liau, 2001; Chan et al., 2010; Russell et al., 2005; Park & Seo, 2006; Keoleian, 1993). There is a trend towards developing simplified LCA-based DFE methods (Chen & Liau, 2001), however even with a more streamlined approach the underlying limitations of the LCA methodology will continue to produce unreliable design tools unless they are addressed.

The early stages of product development have the most uncertainty because of the lack of design data, so there is often not enough information to complete the LCA-based approach goal and scope phase, as the ISO 14040 and 14041 currently outlines it. As a result, simplified LCA approaches are used, which ultimately contribute to more ambiguity in the results (Keoleian, 1993). As previous sections have pointed out, LCA methodology needs further development when it applied to an existing system. Furthermore, LCA methodology needs even more development in order for it to be effectively applied to product design and development so that designers can take advantage of all that a full LCA has to offer (Chang, Lee, & Chen, 2014; Park & Seo, 2006; Klöpffer, 1997). Before developing an approach that fully overcomes the limitations and inaccuracies inherent in LCA methodology, the current state of LCA-based product development and design tools is considered. More specifically the focus of this review is on the concept phase focused design tools that have attempted to tackle problems identified with the underlying LCA methodology.

During the concept design phase of product development there is the greatest opportunity to affect the final product, because after the concept is decided the environmental impacts are essentially solidified (Chiu & Chu, 2012). Due to the lack of certain data during the concept generation phase it requires the greatest amount of assumptions and computations in order to establish the potential environmental impacts. There are both qualitative and quantitative product design and development tools that integrate LCA approaches into the method. Generally, qualitative methods are empirical studies that generate more reliable data collection and data analysis techniques. Meanwhile, quantitative design tools use statistical or data mining methods to gather data that lead to more effective environmental product design (Chang et al., 2014). In Chang et al.'s 2014 review of over 100 LCA-based product development methodological studies care classified into 'development of eco-concepts', 'classification of eco-design', and 'exploration of eco-concepts'. Since this is the most up-to-date and comprehensive text mining based review paper on the topic at hand, the current state of LCA-based product development during the concept phase is based on this classification with some additional input.

The 'development of eco-concepts' entails the decisions of general product information including shape, size, materials, function, and complexity. These elements have a relationship to the final environmental impacts, however since there is no physical product to be tested quantitative prediction is often utilized. Chen and Liau (2001) integrated Artificial Neural Network (ANN) with LCA methodology in order to link conceptual data and environmental impacts. Telenko and Seepersad (2014) developed an LCA-validated method using reverse engineering techniques in order to determine eco-design guidelines based on existing products. While this tool is useful in that is creates a functional basis for assessment, it does not address the underlying issues of ambiguous functional unit definition when completing the LCA.

The concept design category of ‘classification of eco-design’ general entails methodology developed to classify design concepts based on LCA results. Park and Seo (2006) proposed a framework for a knowledge-based approximate life cycle assessment system (KALCAS) for product concept development. This framework helps to identify environmental impact drivers of high-level product attributes by grouping whole products based on environmental characteristics. The limitation of this approach is that it is a physical object-based approach, which limits its ability to compare products that perform the same function by a different workflow. Sousa and Wallace (2006) developed a classification method that uses hierarchical clustering to assign products based on certain features and their association with environmental impacts. However, this method merely uses “meaningful general product concept descriptors” and thus fails to systematically define what product attributes should be used in the classification.

The third concept design category of ‘exploration of design environment’ provides limited methodology development most likely due to its time intensive nature. Heijungs et al. (2010) did however suggest a general modeling framework or ideology that takes a comprehensive view including product specific, life style use, and societal structure perspectives. Chang et al. (2014) suggests “this design process framework can be used to develop more comprehensive theoretical ideas for designers”. In summary, LCA-based concept design methods for product design and development have seen a lot of attention in recent years, but no studies address the underlying issues of the LCA methodology.

The methodology developed in this thesis work aims to create a more standardized approach to LCA goal and scope phase definition as applied to product development. By establishing a more systematic and reliable assessment approach, the framework creates a method that is simple for industry users to understand and implement, easy to update as product evolve, and is more accurate in comparing alternative technologies that provide the same function.

3. Motivation

As worldwide population grows, material needs increase, and resource availability diminishes, it will become more critical to recognize the environmental impacts of product systems in order to mitigate the negative effects. Environmental life cycle assessment has the potential to be an informative tool to many stakeholders. This potential depends on how well the assessment accurately reflects reality and how much confidence there is in the data, assumptions, results and conclusions. Most all LCA case studies that recognize that the ambiguity in goal and scope phase definition leads to a lack of confidence in results make an attempt at formalizing the study functional unit and system boundary definitions. The goal and scope phase is critical to the confidence and comparability of LCA results, but because the ISO framework provides little structure as to how practitioners should progress through this phase, often confidence and accurate comparability is limited. A framework has been proposed by Fumagalli (2012) and Esterman et al. (2012) that integrates system engineering and functional decomposition into the goal and scope phase of an LCA. This framework aims to create an object-oriented LCA model that, when refined and implemented, will significantly improve the current state of environmental assessment. The object-oriented LCA model will most importantly allow the possibility of scaling assessments by user behavior.

In Fumagalli (2012) the proposed framework was applied to existing systems with the function of ‘destroy information’ to demonstrate its usability, steps of implementation, and potential for confidence in comparability. A paper shredder, Bunsen burner, and bin and matches were the systems compared. The initial steps of this study maintain an abstract analysis perspective to ensure that the technology and customer behavior are independent from functional and parameter definition. Fumagalli’s (2012) work uses data without any testing or analysis because the purpose of the work was to illustrate the functionality of the approach and determine potential limitations. To carry out this purpose two phases were used. The first phase demonstrated that the proposed framework is compatible with current LCA software (SimaPro®) and that the methodology is versatile with respect to different use behaviors. The second phase demonstrated that the proposed framework is compatible with LCAs comparing different technologies with equivalent use scenarios.

This initial work “consisted of a classification of issues regarding functional unit, refining the method, developing guidelines and recommended process to be used in the goal and scope phase of LCA, and lastly the application of the recommended framework on a detailed case study to identify issues and determine its utility” (Esterman et al., 2012). Overall, Fumagalli’s (2012) work concluded that the application of the framework was successful in its initial application in terms of the potential of the methodological tool. While the proposed framework addresses functional unit definition, boundary selection, special variation, local environmental uniqueness, and data availability and quality, this work is still at its beginning stages.

Since the proposal of the this goal and scope phase framework, little research has been done to implement or refine the methodology even with its significant potential to increase confidence and comparability of LCA results. Fumagalli (2012) presents a few limitations of the framework implementation, which could present themselves as areas of improvement through further study. These limitations and areas of improvement include:

- Systematic and exhaustive identification of use and scaling parameters
- Prioritization of parameters to improve the versatility of the model
- Framework for determining equivalence of workflows
- Detailed functional decomposition
- Application of the framework to lower levels of the decomposed model

The work presented here will explore further into the implementation barriers of the proposed framework and refine the limitations in order to make the methodology more widely accepted and implemented by LCA practitioners.

4. Problem Statement

The lack of standardization in environmental life cycle assessment methodology as defined in ISO 14040 is an impediment for accurate results and comparability of products. This gap provides an opportunity to propose a framework that specifies a structured standardization in methodology with propositions, which will address current limitations. Since the goal and scope phase of an LCA is the most critical because it effects each subsequent phase and the credibility of results, this is the focus for standardization. Fumagalli (2012) established an initial framework to fill the identified gap in standardization. The initial framework integrates systems engineering tools into the traditional LCA approach in order to enable the unique abilities of adaptability to any use scenario and comparability of any products providing the same function. Since the proposal of this goal and scope phase framework, little work has been done to implement or refine the methodology even with its significant potential to increase confidence in and comparability of LCA results. The degree to which the initial framework will standardize assessment implementation is still limited. These limitations must be thoroughly identified and resolved before an exhaustive methodology framework can be put forth and accepted in the international LCA community of practitioners.

The goal of this work is to continue refining and developing the Dynamic LCA framework as its newly defined object-oriented framework. The primary focus of this study is to establish a systematic approach to defining use parameters to ensure that the use phase is fully captured by the Cumulative Damage Function. In addition, this study aims to refine the current framework to be more precise in terms of terminology and to have a thorough step-by-step implementation guide. By achieving these goals, the object-oriented LCA framework will be farther along in its development as a widely accepted LCA methodology.

5. Proposed Methodology

While standardized assessment can lead to the ability of decisions makers to better recognize associations between product system stages and environmental consequences, it is important to consider that ultimately industry-wide changes along with changes in consumer behavior are the most crucial factors in reducing the environmental impacts of products (Owens, 1997; Rebitzer et al., 2004). This consideration reinforces the need for an object-oriented LCA model that readily accounts for varying use scenarios and product workflows. This type of LCA framework can increase confidence and comparability of results in addition to providing a more applicable environmental assessment tool for product design.

Fumagalli (2012) developed a framework for what we now think of as an object-oriented approach to conduct life-cycle assessment through an iterative process. This framework serves as the starting point for the work presented in this thesis. In this work, the established framework will be applied to a case study in order to improve the methodology, identify shortcomings, and establish its validity.

5.1. Updates to LCA Framework

The object-oriented LCA framework presented in Section 2.4 holds great potential to standardize and improve product life cycle studies. However, that was just an initial work. The refinement of the proposed framework is necessary, and expected, part of the continuous improvement process needed to improve the quality of the methods that practitioners have available to them to implement. While the implementation of a case study may shed light on the need for further refinement, it is expected that the research in this work will focus on four areas for further development:

1. Further refinement of the 'Allocation' function
2. Systematic definition of use parameters and scaling parameters
3. Identification of product system damage multipliers
4. Definition of an explicit methodology for defining use phase energy consumption

Initial literature research will help improve these areas, while the case study implementation will enable a more structured and thorough definition of these methodologies.

5.1.1. Refinement of the ‘Allocation’ function and Cumulative Damage Function

The allocation function as defined in Step 3 of the proposed framework establishes “how much of the defined bill of materials will be quantified for the environmental impact assessment”. The first improvement on this function is in reassessing the terminology. Traditionally the term allocation has been used in life cycle assessments to imply how much of the environmental burdens the practitioner assigns to each of the functions or co-products of a multi-functioning system. The concept of LCA allocation is cited as a common and controversial problem because if a well-defined procedure is not used the assessment results will be incorrect (Reap et al., 2008b). While this particular problem is not addressed in this work, it is important that the terminology used in this remain consistent with standard terminology to avoid possible confusion.

The simple solution proposed in this work is to use the term ‘System Impact’ instead of ‘Allocation’, as seen in equation 1. This better captures the purpose of the function and avoids confusion amongst practitioners. Furthermore, since this function is the most critical component to standardize the LCA goal and scope phase and allows for easy updating of the use phase scenarios it is important that terminology remains consistent and that the functions are user-friendly. In Fumagalli’s (2012) work there seems to be a lapse in effectively conveying the functions in conceptual and mathematic terms. The conceptual function uses the word ‘limit’ in what appears to be a mathematical manner, but in actuality is used to imply the life span of the product up until its end of life whether this be by failure, obsolescence, or lack of need. As an improvement on this potential misperception the ‘limit (L_F, L_{OBS}, L_{NEED})’ term of the newly named ‘System Impact’ function is restated as ‘Product System Life Span’. It is important to note here that while the numerator of this function is clearly defined in a standardized mathematical manner the denominator remains as an assumption laden term. Further work through the implementation of the defined case study will develop a standardized methodical means of calculating the ‘Product System Life Span’ term in order to improve this framework further.

The Cumulative Damage Function is more precisely defined in Equation 2 and is a linear relationship representing the consumed life of the product system. The output is a function of the defined constants in terms of a set unit (a) and a specified use scenario for each parameter (x). The constants would be established through accurate product testing such as life-tests, reliability tests, and accelerated stress tests. For example in the case study presented by Fumagalli (2012) the product system of interest was a paper shredder and each constant was in terms of letter sized paper sheet equivalent. The use parameters of number of cardboard sheets or number of CDs are all scaled to the appropriate letter sheet equivalent. Since the constants are determined by product testing the results of this function will be consistently dependent only on the use scenario input.

Equation 2

$$\begin{matrix} Cumulative\ Damage \\ Function \end{matrix} = z\left(\sum_{i=1}^{n} a_i \cdot x_i\right)$$

Where:

z = total system damage multiplier

n = the number of scaling parameters defined

a = use parameter dependent constant scaling parameter

x = use scenario parameter

Equation 3

$$\begin{matrix} System \\ Impact\ (\%) \end{matrix} = \frac{Cumulative\ Damage\ Function}{Product\ System\ Life\ Span} \times 100$$

As previously state, more work will need to be done in order to further refine the System Impact function. However, at this stage in this research the functions are now successfully defined in a consistent manner that can be easily implemented by any LCA practitioner.

5.1.2. Systematic Definition of Use Parameters and Scaling Parameters

The ability for the Cumulative Damage Function to accurately capture a product system use phase is contingent upon the thorough and complete definition of the use phase parameters, $x_{i \to n}$. The initial Dynamic LCA framework is a starting point, but does not attempt to standardize the process of identifying all use parameters. This section will propose a method to systematically identify the use and scaling parameters of a product system. It is important to note that Fumagalli (2012) set forth some criteria that the parameters must meet in order for them to operate appropriately in the Cumulative Damage Function. These criteria must be considered in this proposed methodology and they include that the use parameters are:

- In terms of either system level input or output flows
- Able to correlate with the ultimate impacts generated by the system
- Scalable by consumer use patterns

Due to the lack of a methodology and the significant importance of a product's use stage, Telenko and Seepersad (2014) developed a preliminary approach to scoping use scenarios based on usage context factors. Their scoping approach does have some limitation in its application to the object-oriented LCA framework proposed in this study. These limitations include that the method described in their work is in the context of a static functional unit and was developed for specific application to energy consumption. However, the general structure and usage context factors of their scoping approach provide the initial framework for systematically defining the scaling parameters for the Cumulative Damage Function. Their general structure includes establishing a parameter reference checklist, which provides a sanity check throughout the definition process, and is based on three usage context factors: product, situational and human (Telenko & Seepersad, 2014).

Product factors are those that describe the technical operating parameters and product system features (i.e. maintenance, aesthetics, and functionality). Situational factors are those that describe properties of the task being completed and the surrounding environment, which change the behavior of the product system or user (i.e. task association and location of use). Lastly, human factors are those that describe user dependent aspects that effect task specifications, environmental selection, and operating procedures (i.e. user qualities). Telenko and Seepersad (2014) compile the checklist by conducting a literature review and brainstorming all of the possible elements under each of these factors. While the resulting list under their method is mainly helpful in further scoping the parameter identification, it does not provide an exhaustive, nor complete, set of parameters. Rather, the list of parameters is useful in prompting brainstorming in subsequent steps and provides a sanity check as the parameters are developed through the more systematic approach proposed here.

The systematic method proposed in this section is a unique approach to defining use parameters and scaling parameters under each of the three usage context factors; product, situational, and human. It is important to consider all three categories of factors because product systems cannot function based on any one of these categories alone. By considering the product, human, and situational factors, this systematic method can ensure that all of the primary use parameters are defined and ultimately the Cumulative Damage Function accurately captures the use phase of the product system. There is no way, however, to ensure that this approach will be exhaustive in defining any secondary use parameters such as aesthetics or entertainment. This shortcoming is accepted because non-physical secondary parameters cannot be captured as engineering metrics and thus there is no way to accurately model them. This is not to say that these secondary metrics are not important to consider in product design, but they will not be addressed in this environmental impact focused method.

Overall, this method integrates several systems engineering tools so that each new step is an extension of the last while terminology and the underlying thinking remains consistent. The method to systematically define use parameters and scaling parameters as defined in Sections 5.1.2.1, 5.1.2.2, 5.1.2.3., and 5.1.2.4 will be integrated as the new Step 2 in the object-oriented LCA methodology.

Figure 4 illustrations how the proposed methodology steps integrate into the overall framework and pre-established methodology steps.

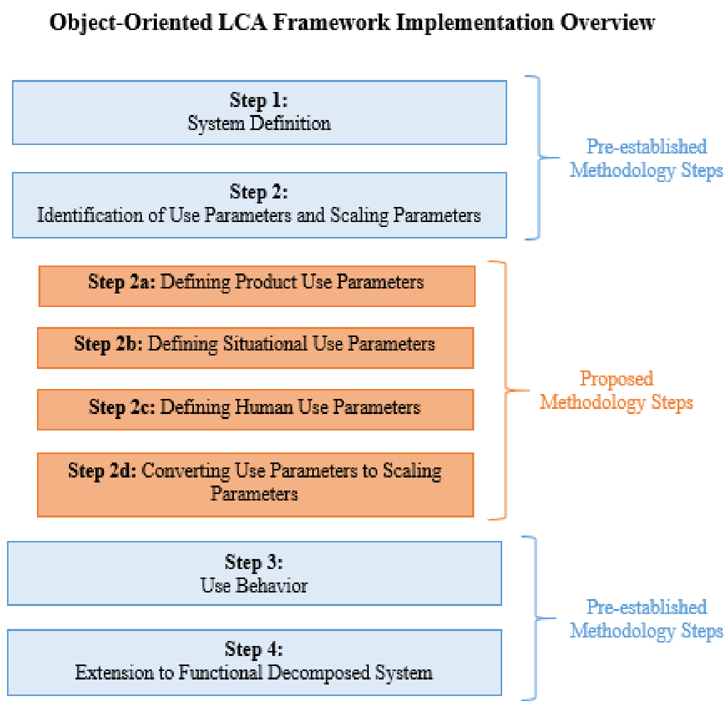

Figure 4: Integration of Proposed Methodology Steps to Define Use Parameters and Conversion to Scaling Parameters into the Pre-established Framework Steps

A nail clipper product system example is used in order to demonstrate each of the proposed methodology steps. First, the functional use phase boundaries are defined according to Step 1 in Section 2.4.1. The function of a nail clipper is defined as 'remove excess length of fingernail' and the system level input and output flows, interfacing systems and enclosing system are depicted in Figure 5.

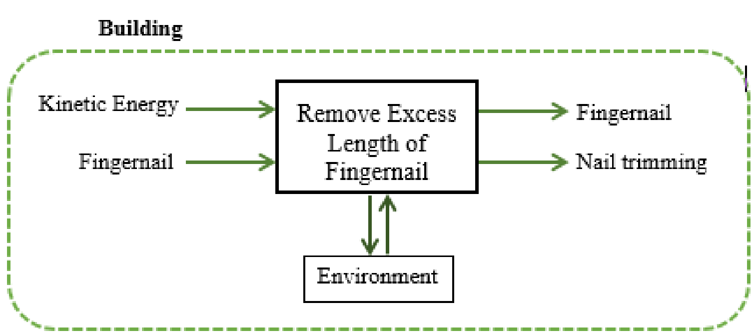

Figure 5: Example Functional Definition of Nail Clipper Product System

The following sections describe the proposed methodology steps 2a, 2b, 2c and 2d from which product, situational, and human scaling parameters can systematically be defined such that the Cumulative Damage Function completely captures the use phase. Each proposed step is applied to the example nail clipper system as defined in Figure 5.

5.1.2.1. *Step 2a: Defining Product Use Parameters*

In order to systematically define the LCA use phase technical product scaling parameters, functional analysis is used. Functional modeling is often used as a design activity to develop models of devices, products, objects, and processes based on the primary function and the function of the subcomponents (Erden et al., 2008). More specifically, functional decomposition is considered a well-established systems engineering tool and is a systematic way of determining all subsystems of a particular product (Umeda et al., 1990). It is proposed in this framework that by decomposing the system functions and determining the appropriate engineering metrics that quantify the lowest level subfunctions, all technical product scaling parameters will be identified. The functional decomposition tool fits well into this proposed object-oriented LCA framework because of the consistency in defining a product system based on a technology-independent primary function as outlined in Step 1. The vocabulary necessary to capture the function and sub-functions, as applied to the context of this LCA framework, is called functional-concept-ontology. This term captures the appropriate framework and language needed in order to model the functionality of the system from a subjective viewpoint (Erden, et al., 2008).

As part of Step 1 of this methodology the primary function of the system of interest is identified along with its associated material and energy inputs and outputs and interfacing systems. The LCA use phase of a product system depends on both system and subsystem level functionality, however the systems engineering approach in Step 1 only identifies the system level functionality. This is why functional decomposition in this Step 2a is critical in defining a use phase because it will help define the subsystem level functions that otherwise would go overlooked. Essentially the technical product scaling parameters are those that enable the transformation of system material and energy inputs to system material and energy outputs.

For this methodology, the functional decomposition is completed down to the level at which the next level would need to assume technology solutions to complete the analysis. While ultimately the specific product technology will be assessed, at this point in the methodology is it important to remain solution independent so that the comparison of technologies is unbiased. The lowest level of subfunctions before specific technology solutions need to be considered, is the appropriate level of functionality to identify in order to define the product scaling parameters. Figure 6 shows the functional decomposition of the 'remove excess length of fingernail' example. In this simple example, the second level of decomposition is the lowest level at which the next level would need to assume a specific technology solution.

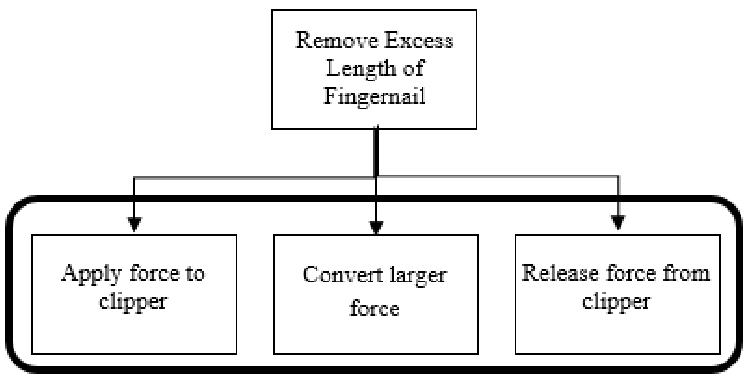

Figure 6: Example Functional Decomposition of Nail Clipper Product System

Once the appropriate subfunctions are identified according to the functional decomposition process, the subfunctions must be translated into engineering metrics. These engineering metrics are the technical product use parameters. Engineering metrics measure both the degree of effectiveness of the product and the processes, which is why the metrics are not always easy to define. To help effectively define the engineering metrics in this methodology the LCA practitioner should think about the aspect that makes the sub-function effective and the characteristic that leads to the desired results of the sub-function (Kasser & Schermerhorn, 1994). Table 1 demonstrates how the example nail clipper subfunctions from Figure 6 are translated into the engineering metrics or product use parameters.

Table 1: Example Mapping of 2nd Level Decomposition Sub-functions to Use Parameters

Subfunction	Product Use Parameter
Apply force to clipper	Force applied to clipper
Convert larger force	Force applied to nail
Release force from clipper	Force released from clipper

It is important to keep in mind that the use parameters must all eventually be scaled to the same unit in order to create true scaling parameters in the Cumulative Damage Function. Once all of the technical product scaling parameters are identified they must be quantified. Product testing is the most effective way of quantifying the scaling parameters to the same unit. However, this type of intricate product testing is not always possible during product development or when conducting an LCA because of complexity of the product, lack of accessibility to the product, and/or time constraints. If product testing to quantify the scaling parameters is not available the scaling parameters can be quantified based on manufacture specifications, literature findings, and engineering judgment.

This methodology's reliance on the accuracy of functional decomposition sheds light on the question as to whether or not there is always a consistent way of decomposing a function. Functional decomposition is a widely used and well known design tool used in system engineering, however it is often implemented in a haphazard way such that the results are undesirable (Coulston & Ford, 2004). Not only is it implemented in a haphazard way, but also the actual process of performing functional decomposition is also subjective from one practitioner to another based on opinion, knowledge, and experience. Overcoming this weakness is outside the scope of this study, however the case study will test the sensitivity of the final results to functional decomposition definition. In parallel effort to this study, Gadre (2016) further developed the use of functional decomposition to support the modular application of the object-oriented LCA methodology. Gadre (2016) demonstrates that by implementing this object-oriented LCA method at all levels of the functional decomposition, alternative technologies and use scenarios can easily be compared without causing changes to other aspects of the system.

Continuing with the proposed methodology of systematically defining use parameters, once the technical product use parameters are defined, the situational and human scaling parameters must also be defined by following step 2b and 2c of this methodology. The usability and completeness of this full methodology is tested in a case study in Section 6 of this Thesis.

5.1.2.2. *Step 2b: Defining Situational Use Parameters*

Situational and human scaling parameters must be defined because product scaling parameters only capture the technical aspects of the product system use phase. The situational and human parameters capture the more dynamic factors in the use phase. Dynamic is meant here in the sense that once a product system is chosen the situational and human parameters can be scaled by nearly an infinite number of use scenarios. However, once a product system is chosen the product parameters will only be scaled by the nearly static technical metrics. The cases where product parameters will be scaled are when there are different setting options (such as speed) or if over time the functionality of the product diminishes.

Situational scaling parameters in this methodology are systematically defined based on the interfacing systems to the primary product system, as defined in Step 1. This steps' dependence on how accurate the interfacing systems are defined in the previous step, highlights the importance of being thorough and deliberate in each step of this methodology as each step builds on one another. The interfacing systems as defined in Step 1 are those physical systems that interact and effect the function defined as the system of interest. In order to determine the situational scaling parameters the factors of the interfacing systems that affect the system of interest must be identified. The factors of the interfacing systems are the aspects of the task and the environment that are quantifiable. Aspects of the task include the states of inputs and outputs such as flow rate of consumables and input and output qualities. Aspects of the environment describe the state of the surrounding environment such as temperature, humidity, and moisture content. While an interfacing system may be common for many systems, this does not necessarily mean that they produce the same factors affecting the system of interest. For example, the environment will always be an interfacing system, but the factors of the environment that effect the system of interest will not always be the same.

Table 2 shows the situational use parameters defined for the example 'remove excess length of fingernail' product system. In this example, the 'Environment' was the only defined interfacing system. The aspect of the task and environment that interacts with the product system includes the fingernail, which can be quantified by thickness and hardness. Therefore, the situational use parameters are defined by the metrics of fingernail thickness and hardness.

Table 2: Example Situational use parameters and the associated interfacing system of the 'remove excess length of fingernail' system

Interfacing System	Situational Use Parameter
Environment	Fingernail thickness at point of cutting
	Fingernail hardness

Generally, situational parameters will not be technical based, which makes defining these parameters much more brainstorming based as compared to the product parameters. This means that it is especially pertinent that the practitioner takes careful consideration when defining the task and environmental factors that translate to the situational scaling parameters, because there is more room for error in this step of the methodology.

The task and environmental factors of the interfacing systems are identified as situational use parameters. Next in Step 2d, these use parameters will be converted or measured as quantifiable engineering metrics. These engineering metrics make up the set of situational scaling parameters. The scaling parameters scale each of the use parameters to a common unit. Step 2d describes in detail the process for converting use parameters to scaling parameters.

5.1.2.3. *Step 2c: Defining Human Use Parameters*

Just like the situational scaling parameters, defining human scaling parameters is mostly brainstorming based and not as technical based as defining the product parameters. The human scaling parameters in this methodology are some of the aspects associated with user behavior and patterns that correspond to efficiency. Inherently, these aspects of the use phase are also the most variable from one user to another and therefore the root cause of ambiguity in use phase definition. The ability to thoroughly define these human factors and ultimately scale them by any use behavior is one of the most important motivations for developing and demonstrating validity of this methodology.

Human factors are those that describe aspects of the user and their patterns of interaction with the product system. As discussed, this does not necessarily mean that a human is the operator, but there must be some entity giving user input to the product system otherwise it would not, by definition, have any quantifiable functions. This methodology step, when applied to systems with user input, provides a framework for defining the human use parameters as inputs for the Cumulative Damage Function.

Aspects of the user that ultimately correspond to human use parameters include task specification, environmental selection, and operating procedures (Telenko & Seepersad, 2014). While not all human use parameters fit neatly into one of these categories it is important to consider all three aspects. For example, the level of wear on the product system is often defined as a human use parameter and it is dependent on task specification, environmental selection, and operating procedures. Generally, task specifications take into consideration preferences when performing a task, environmental selection takes into consideration conceptually where the task is performed, and operating procedures takes into consideration specifically how the user operates the product system. Environmental selection considerations in this step differ from the environmental interfacing scaling parameters in the previous step because here the practitioner must consider holistically where in the world the function is being performed. On the other hand, environmental interfacing scaling parameters capture the physically surface interacting with the system of interest.

When defining human use parameters the practitioner should consider parameters that fit into all three categories of user aspects including task specification, environmental selection, and operating procedures. Table 3 shows the human use parameters defined for the example ‘remove excess length of fingernail’ product system.

Table 3: Example human use parameters and their associated user aspect category of the 'remove excess length of fingernail' system

Category	Human Use Parameter
Task specification	Time in use
Environmental selection	Maintenance of system
Operating procedures	Efficiency during use

Through the iterative process of developing this proposed methodology, it was determined that human use parameters can quantify the efficiency of the system. Therefore, the human use parameters defined in Step 2c are then converted to system damage multipliers as outlined in Section 5.1.3 of this study.

5.1.2.4. *Step 2d: Converting Use Parameters to Scaling Parameters*

Once all use parameters are defined, the next step in systematically defining the scaling parameters is this *Step 2d: Converting Use Parameters to Scaling Parameters*. Through the iterative process of developing this proposed methodology, it was determined that product use parameters are the natural inputs for system energy, situational use parameters help quantify the consumed life of the product and human use parameters help quantify the system efficiency as damage multipliers. Figure 7 shows a visual representation of what each use parameter type converts to and helps quantify. Ultimately, all of the use parameters help to effectively quantify the product system consumed life of the use scenario being model. The energy factors are inputs to quantifying the use phase energy. The scaling parameters and damage multiplier are inputs to the Cumulative Damage Function.

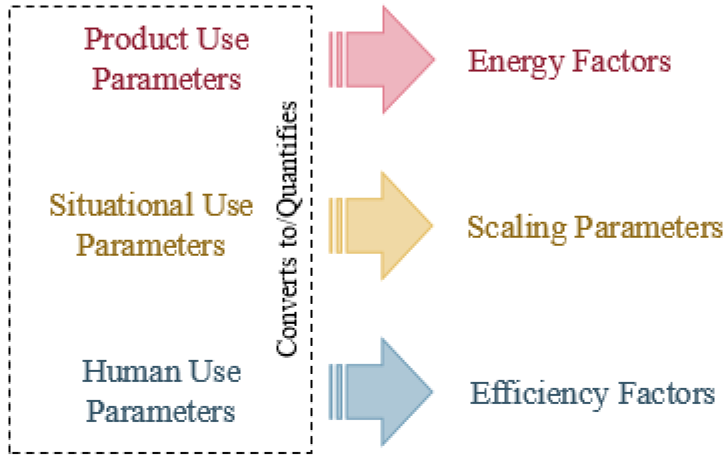

Figure 7: Types of use parameters and which factors they convert to and help quantify

This step takes the situational use parameters defined from *Step 2b* and qualitatively converts them into the scaling parameters before quantifying them as scaling parameters. Scaling parameters are inputs to the Cumulative Damage Function, are the basis for modeling the product system use phase, and ensure that the model can be scaled to any use scenario in a consistent and reliable manner. Equation 4 reiterates the Cumulative Damage Function used in this methodology and highlights which variables are the scaling parameters.

Equation 4

$$\begin{matrix} \textit{Cumulative Damage} \\ \textit{Function} \end{matrix} = z\left(\sum_{i=1}^{n} a_i \cdot x_i\right)$$

Where:

z = total system damage multiplier
n = the number of scaling parameters defined
a = use parameter dependent constant scaling parameter
x = use scenario parameter

Scaling parameters are the constant values, which fundamentally enable use scenario parameters to be scaled to a common unit. When the Cumulative Damage Function is scaled to a common unit, it is able to quantitatively represent the use phase of a product system. The use scenario parameters defined from *Step 2b* cannot be inserted directly into the Cumulative Damage Function without first following *Step 2d* to scale the use parameters. This scaling using the constant scaling parameters is necessary to create a consistent unit and to ensure that the use scenario parameters contribute the appropriate impact to the overall Cumulative Damage Function.

The discretion of the practitioner is used in order to convert the situational use parameters to scaling parameters while following some simple guidelines outlined here. The first important guideline to follow before starting to convert use parameters to scaling parameters is to consider whether a use parameter should actually be classified as an damage multiplier rather than a scaling parameter. The identification of system damage multipliers is discussed in full in Section 5.1.3. Put simply, a damage multiplier is an element of the system that quantitatively describes the state or quality of the function being performed. Use and scaling parameters on the other hand quantitatively describe a characteristic of the physical product.

The second guideline to consider is if multiple use parameters correlate to one scaling parameter than that scaling parameter should only be identified once to ensure there are no double counting of impacts. Specifically, it will be common for more than one product use parameter to correlate to a single scaling parameter because product parameters are defined based on sub functions and often times subfunctions correlate to a single metric that the user interfaces with. When using this methodology for product development it is important that all product use parameters be converted to scaling parameters separately so that each sub function can be manipulated during concept initiation. However, when this methodology is used for conducting an LCA study multiple product parameters can be converted to a single scaling parameter.

The third guideline to consider is the tense of word choice of the scaling parameters. This guidance, simply put, intends to remind the practitioner that the tense of word choice when qualitatively defining the scaling parameters should be consistent. This is so that quantification of scaling parameters is easier and consistent.

The fourth and final guideline to consider is what unit is appropriate to scale the parameters to. The unit choice is depended on the product system under analysis and should always be a unit that parameters can be scaled to based on product or situational testing. By quantifying scaling parameters based on testing the practitioner can be confident in the accuracy of the Cumulative Damage Function and the modeling of the product use phase. Table 4 shows the situational use parameters converted to scaling parameters for the example ‘remove excess length of fingernail’. In this example, the common scaling unit is defined as 0.45mm, 2.25 mohs fingernail clipped. This unit describes the average thickness and hardness of a fingernail. When modeling the use scenario of a nail clipper the number of different fingernails clipped will all be scaled to this common unit. Table 5 shows the quantification of scaling parameters. In this example, the quantification of scaling parameters is based off of scholarly research of fingernail thickness and hardness. Since the common unit is an average thickness, average hardness fingernail, thinner softer nails are equal to less than one and thicker harder nails are equal to more than one.

Table 4: Example Use Parameter Conversation to Scaling Parameters and Scaling Unit Definition of the 'remove excess length of fingernail’ system

Situational Use Parameter	Scaling Parameter
Common unit: 0.45 mm, 2.25 mohs fingernail clipped	
Fingernail thickness at point of cutting *https://www.ncbi.nlm.nih.gov/pubmed/11301643	Thin nail (0.4 mm)
	Average nail (0.45 mm)
	Thick nail (0.5 mm)
Fingernail hardness *https://geology.com/minerals/mohs-hardness-scale.shtml	Soft nail (2.0 mohs)
	Average nail (2.25 mohs)
	Hard nail (2.5 mohs)

Table 5: Example Constant Scaling Parameter Quantification of the 'remove excess length of fingernail' system

Scaling Parameter	Constant
Common unit: 0.45 mm, 2.25 mohs fingernail clipped	
Thin soft nail	0.79
Thin average hardness nail	0.89
Thin hard nail	0.99
Average thickness soft nail	0.89
Average thickness average hardness nail	1
Average thickness hard nail	1.11
Thick soft nail	0.99
Thick average hardness nail	1.11
Thick hard nail	1.23

As a whole, this methodology puts into place guidelines and points of reference so that the LCA practitioner can ensure that they have been as exhaustive as possible in defining all scaling parameters. While Step 2b and Step 2d allow some subjectivity in defining the situational and human scaling parameters, they provide a framework so that the brainstorming process is not haphazard. In addition, by following the guidelines in these systematic steps there is more structure to the goal and scope and use phase definition than any other currently proposed LCA methodology.

5.1.3. Identification of System Damage Multipliers

By following the steps outlined in Section 5.1.2 the use and scaling parameters are systematically defined for the product system of interest. This method of systematically defining the system use parameters and converting them to scaling parameters is the main contribution of this research. Prior to this research study, scaling parameters were defined solely based on practitioner's best judgment. By adding a systematic methodology around scaling parameter definition there can be confidence that the Cumulative Damage Function accurately represents the product system use phase. In addition, as this systematic methodology was developed the necessity of distinguishing system damage multipliers from scaling parameters was identified. The present section defines how damage multipliers differ from scaling parameters, the importance of identifying damage multipliers, and guidelines for quantifying damage multipliers.

A damage multiplier in this methodology is an element of the product system that qualitatively describes the state or quality of the function being performed. On the other hand, scaling parameters quantitatively describe a characteristic of the physical product or interfacing systems. The clear distinction here between the two elements of this method is that damage multipliers describe qualitative aspects of user efficiency while scaling parameters describe quantitative aspects. Scaling parameters can be technical attributes of the system such as power generated by the product.

Damage multipliers describe how the user tendencies and patterns affect the scaling parameters on a scale from minimal damage to greatest damage. Minimum damage would be a scenario when a function is performed with no excess use or wear on the product and the system is precisely maintained. A greatest damage multiplier would be a scenario when a function is performed with excess use and wear on the product and the system is precisely maintained. It is important to identify damage multipliers because while a scaling parameter of 'power generated' quantifies the power the system can deliver in any single moment it does not take into account the user variability's effect on that power. Damage multipliers account for the user variability of the scaling parameters, which is critical to modeling an accurate and realistic LCA use phase.

The first step in identifying the system damage multipliers is to define the human use parameters in *Step 2c: Defining Human Use Parameters* and evaluate if any other use parameters should be reconsidered as damage multipliers in *Step 2d: Converting Use Parameters to Scaling Parameters.* As part of *Step 2d*, the guidelines dictate that the practitioner must consider if any use parameter should instead be considered a damage multiplier because of qualitative parameter characteristics. It is postulated that in many product systems nearly all human use parameters would be reconsidered as damage multipliers. This is because human use parameters identify the factors of a system that are affected by user input, which correlates strongly to the definition of system damage multipliers. After evaluating the damage multipliers identified from *Step 2d*, the next guideline for identifying the system damage multipliers is for the practitioner to go through each scaling parameter and ask 'what aspect of user behavior impacts this scaling parameter?'.

The answer to this question or the aspect of user behavior will be a system damage multiplier. Generally for a product system there will be damage multipliers that correlate to the technical aspects of the product, the use of consumables, optimization of the product features (if applicable), maintenance of the product system and time in use. The number of damage multipliers needed to accurately describe the product use phase will depend on the relative complexity of the product system. The more complex a product is in terms of features and moving parts, the greater the number of damage multipliers.

Once all damage multipliers are identified, the damage must be quantified in terms of a range from least to greatest effective. The damage multiplier range values are always unit-less because they reflect the quality or state by which the use parameters function is performed. The least total damage for any system is always a value of one because this reflects a use scenario where the use parameters are able to perform to their full function and no additional environmental impacts are incurred in the use phase due to user inefficiencies. The higher the total damage value the more environmental impacts are associated with the use phase because user inefficiencies cause the system to perform sub-optimally. It is postulated that the more human input needed for a system to function, the less efficient the system will be and therefore the greater the total damage multiplier will likely be for that system. This is because the more human input needed for a system to perform the greater opportunity for user error or inconsistent behavior. The case study implemented in this research will demonstrate the integration of this new methodology aspect into the current framework and show how the efficiency of product use could have a large impact on the overall environmental impacts of the system.

Just as with the quantification of scaling factor constants, when implementing this methodology for actual product design or full LCA purposes, the damage multiplier use scenario values should be identified through testing or scientific research to ensure the most reliable results. The total damage value is the product of individual damage multiplier values as shown in Equation 5. Equation 6 reiterates how the total damage multiplier (*z*) is used in the Cumulative Damage Function.

Equation 5

$$\begin{array}{c} Total\ System \\ Damage\ Multiplier\ (z) \end{array} = \prod_{i=1}^{m} z_i$$

Where:

m = the number of damage multiplier defined
z = damage multiplier

Equation 6

$$\begin{array}{c} Cumulative\ Damage \\ Function \end{array} = \boldsymbol{z} \left(\sum_{i=1}^{n} a_i \cdot x_i \right)$$

Where:

***z* = total system damage multiplier**
n = the number of scaling parameters defined
a = use parameter dependent constant scaling parameter
x = use scenario parameter

To demonstrate the application of identifying damage multipliers, Table 6 shows the nail clipper product system example human use parameters and how each parameter translates into an damage multiplier. No other product or situation use parameters in this example are identified as damage multiplier. The ‘time in use’ human parameter is used as an input to quantify the potential energy use of the product system, therefore is not considered a damage multiplier to ensure there is no double counting of impacts.

Table 6: Example damage multiplier identification of the 'remove excess length of fingernail’ system

Human Use Parameter	Damage Multiplier
Time in use	N/A (Energy Input)
Maintenance of system	Sharpening of cutting edge
Efficiency during use	Use of full cutting edge

Table 7 shows the nail clipper product system example quantified damage range for each of the two identified damage multiplier. When working through this example is was clear that quantifying a binary, yes or no, damage multiplier the quantification is one for optimal use and 2 for non-optimal use. For non-binary damage multipliers the quantification is a more complex. When implementing on a case study, product testing or scientific research are the best way to quantify these damage multiplier. For the purpose of this example, a best estimate is used for quantifying the damage multiplies to demonstrate the implementation.

Table 7: Example damage multiplier quantification of the 'remove excess length of fingernail' system

Damage multiplier	Parameter	Use Scenario Damage Multiplier Range
Sharpening of cutting edge	z_1	1 – 2 (Sharpened after every use – Never sharpened)
Use of full cutting edge	z_2	1 – 2 (Uses the full cutting edge – Only uses portion of cutting edge)

5.1.4. Establishing a Methodology Step for Use Phase Energy

While the original Dynamic LCA methodology established in Fumagalli's (2012) work does identify and implement a means of modeling the energy used during a product's use, it does not identify energy modeling as an explicit methodology step. The intent of the update identified in this present work is to add the modeling of use phase energy as an explicit step in the methodology and to add some guidance around this modeling. It is recognized that this explicit step is needed so that the practitioner does not overlook the modeling of use phase energy. Once all scaling parameters and damage multipliers are defined by following *Step2a – 2d*, *Step 3: Quantifying Use Phase Energy* can be carried out.

5.1.4.1. *Step 3: Quantifying Use Phase Energy*

The quantification of use phase energy applies to any product that requires a power supply to function. If the product system of interest does not rely on any power supply to function than this step can be skipped. If the product system of interest relies on a battery for its source of energy, the battery component should be treated as a consumable. If the product system of interest does rely on an electricity source to function than in order to quantify the total use energy, each energy setting must be identified. For example, a desktop printer system has 3 energy states including, off, standby, and operating, in which different amounts of energy is used during each state. Then the power associated with each of these energy states must then be determined because energy is a function of power multiplied by time in use. While power is a constant value for a given technology in each of the energy states, the time in use of each of the different energy states will vary for each use scenario identified. It is important to note that the time factors (i.e. time in off, time in standby, time operating) are associated with calculating use phase energy and are identified as damage multipliers. Identifying time for both of these applications will not double count impacts because time in these two applications will help identify two unique impacts. In the case of time used to calculate energy impacts, the factor of time is helping determine the environmental impacts associated with energy use for a specific use scenario. In the case of time used as a damage multiplier, the factor of time is helping determine the environmental impacts associated with the product materials, manufacturing, and transport for a specific use scenario. The amount of time that a use scenario dictates is directly proportional to the amount of energy consumed and percentage of the product life span consumed.

In order to calculate the use phase energy in kilowatt-hours (kWh) Equation 7 must be followed. If power is not in kilowatts it must be converted appropriately and if time is not in hours it must also be converted appropriately. The output of this equation is the amount of energy used in a specific use scenario and is directly input into the LCA model to capture the environmental impacts associated with use phase energy.

Equation 7

$$Use\ Energy\ (kWh) = \sum_{i=1}^{n} y_i \cdot t_i$$

Where:

n = the number of energy states

y = power (kW) at given energy state

t = time (h) in use in given energy state

6. Case Study

6.1. Overview and Product System Choice

The product system for this case study is chosen from common household and workplace appliances based on identified criteria. While virtually any product system could be chosen for this case study, the identified criteria must be met in order to demonstrate the effectiveness of the proposed methodology. The first set of identified criteria listed in Table 8 are characteristics of the system itself and aim to ensure the selected product system can be compared to other technologies and compared to other use scenarios. Comparability to multiple technology solutions carrying out the same primary function and comparability of multiple end-user scenarios are primary capabilities of the object-oriented LCA framework. The first set of identified criteria also ensures the selected product system has some functional complexity and does not add difficulties to implementation as a multifunctional product system. These characteristics ensure that the product system is complex enough to demonstrate the capabilities of the proposed framework, but not excessively complex such that it is a multifunction system. The analysis of potential product systems against the target criteria in Table 8 can be seen in Appendix A. The second set of identified criteria listed in Table 9 are intended to ensure a product system is selected that does not have considerable LCA study related constraints. By ensuring the product system does not have characteristics that cause difficulties or nuances in LCA studies, this case study can focus on demonstrating the effectiveness of the proposed goal and scope methodology.

Potential case study products were initially identified as household and workplace appliances since these products are common and widespread. This list was comprised of thirty-four different products. The initial refinement of these common product systems were based on meeting all of the criteria set for the most effective test cases as defined in Table 88. This assessment was done on a ‘yes’(Y) ‘no’(N) basis since there is no tolerance for a product system not meeting a criteria, only products that received all ‘yes’ scores were assessed further. The criteria of ‘Ideal complexity of system’ with a target of ‘existence of idea # of moving parts’ is a criteria has slight ambiguity to it in order to enable the ruling out of systems that are too simple or too complex for optimal case study results. For example a can opener traditionally has few moving parts and is thus too simple because there will be few use parameters to define and therefore limited demonstration of the capability of the Cumulative Damage Function. The outcome of the first product system refinement can be seen in Appendix A**Error! Reference source not found.**. The product systems that received 'Y' for all criteria were then further refined based on meeting the greatest number constraint targets as defined in Table 99.

Table 8: Characteristic target criteria for system selection

Criteria	Target
Availability of different technologies providing the same function	At least two other technologies
Multiple common use scenarios	At least two other use scenarios defined
Reasonable complexity of system[1]	Sufficient # of moving parts
Single function product system	Product only has 1 main function

[1] The definition of complexity adopted in this work is that it is comprised of a quantity metric and a difficulty metric. In order to assess this the number of moving parts was used a rough proxy to capture both. It is understood that this metric is not without its flaws.

Table 9: Characteristic target criteria for final system selection (based on LCA constraints)

Constraint	Target
Co-product allocation	No known co-products produced
Product Consumables	Easy to define consumables outside the system boundaries
Non-quantifiable or difficult-to-quantify functions	Fewer than 3 non-quantifiable or difficult-to-quantify sub-functions (i.e. aesthetics, entertainment, learning, etc.)

Table 10: Product System Choice by LCA Constraint Refinement

Criteri	Co-product Allocation	Product Consumables	Non-quantifiable functions
Target Product	No known co-products produced	Easy to define consumables outside system boundaries	No non-quantifiable or difficult-to-quantify sub functions
Printer	Y	Y	Y
Paper Shredder	Y	Y	Y
Lawn Mower	Y	N	Y
Coffee Maker	Y	Y	N
Jig-Saw	Y	N	N
Vacuum Cleaner	Y	Y	Y
Toaster	Y	Y	Y
Juicer	Y	Y	N

After assessing each product system based on the case study criteria and general LCA constraints it became evident that multiple common household products could be used for this case study. Table 10 shows the final analysis of product systems against the characteristics in Table 8 and Table 9. These products include a printer, paper shredder, toaster, and vacuum cleaner. The final selection of a product system is based on the availability because without a thorough bill of material and SimaPro data, the Cumulative Damage Function will be nearly impossible to implement with sufficient credibility. After analysis of the current data availability, the primary product system chosen for this case study is a vacuum cleaner.

By choosing the product system with the fewest LCA constraints and greatest data quality the need for assumptions in the goal and scope phase is minimized. This is an ideal case because the greater the number of assumptions, the greater the inconsistencies in assessment results. Since the ultimate goal is to increase comparability, confidence, and consistency in LCA results a vacuum cleaner is a good product system for this case study.

Additional confirmation that a vacuum cleaner is good choice for conducting a thorough case study using this proposed methodology is that the European Commission has recently implemented an eco-design regulation (Directive 2009/125/EC) to improve the environmental performance of household vacuum cleaners, among other household products. There are an estimated 200 million household vacuum cleaners used in the European Union (EU) alone, which consumer 18.5 TWh of electricity every year. Gallego Schmid et al. (2016) conducted a through life cycle assessment by which the environmental impacts of current household vacuum cleaners were compared to the potential future impacts of vacuums following the eco-design regulation and WEEE directive. Results of this study indicated that by 2020 the full implementation of the eco-design regulation in combination with the WEEE directive, could amount to a 20%-57% reduction in environmental impacts of household vacuum cleaners in the EU (Gallego-Schmid et al., 2016). The methodology presented here could go a long way towards enabling household vacuum companies to easily implement eco-design concepts and fulfill the potential environmental savings revealed in Gallego-Schmid et al's (2016) study. Furthermore, since the EU Directive 2009/125/EC establishes eco-design legislation for many other household products, an increasing number of product development teams will need to consider environmental impacts during concept initiation. The methodology proposed and demonstrated in this research can be a valuable, easily implemented, and reliable tool for product development teams to use for eco-design.

6.2. Object-oriented Life Cycle Assessment Application

The methodological framework outlined in Section 5 is applied to the case study system selected in Section 6.1, a vacuum cleaner. Conducting a case study with this product system will demonstrate the usability and applicability of the methodology using current modeling software, SimaPro®. It is important that the methodology be applicable using current modeling software because otherwise it would be virtually useless for the foreseeable future if this methodology relied on new modeling software to be developed. In addition, the implementation of this case study will demonstrate that exhaustively defining the use parameters that comprise the use phase will lead to more reliable results when using this methodology. The initial Dynamic LCA framework proposed by Fumagalli (2012) was critical to the further development of the method because it demonstrated the usability of the method using SimaPro®. However, the initial proposal did not provide a method of systematically defining use parameters which can lead to limited confidence in the results generated using the initial framework. By systematically defining the use parameters the practitioner can have greater confidence that the use phase is properly represented in the LCA results. Of course, there will always be some uncertainty in LCA results because of database data quality, human error, and other aforementioned constraints, but this framework helps to minimize this uncertainty. In summary, the methodology proposed and implemented in this case study ensures that the inputs to the LCA SimaPro® model are comprehensive and functionally modeled so that the outputs of the model are reliable and easy to update.

The vacuum product used for this case study is a Eureka Quick Up vacuum. This specific product was chosen because of accessibility to data. In order to be as methodical as possible and demonstrate applicability to industry standards the ISO 14040 and 14044 LCA standard were followed when implementing this case study. It should be noted that all guidelines were followed from these standards except that only one environmental indicator was analyzed (kg CO2 eq.) and a third party peer-review was not conducted. These guidelines were not followed in this case study because of the project scope and intended audience of this research. However, due to these distinct differences this study is not claiming to be an LCA as defined by ISO, but does follow the general guidelines and steps defined by ISO and therefore is referred to here as an LCA.

First, the Eureka Quick Up vacuum is assessed using the proposed object-oriented LCA goal and scope methodology and carried out with the proceeding traditionally defined inventory analysis, impact assessment, and interpretation steps. Second, the same Eureka Quick Up vacuum, with all the same corresponding product assumptions, is assessed using the traditional goal and scope method as outlined by the ISO standard. The usefulness of this test case comparison is to compare ease of use, ease of implementation, and the ability of each method's model to be altered to different use scenarios. At any stage of the product life cycle, industry application of environmental analysis introduces an inherent time constraint on implementing an LCA. Therefore, comparison of the proposed methodology to the traditional methodology in terms of initial and long-term time investment, in additional to accuracy, is significant for industry application. In the proceeding sections, the steps of an LCA are carried out on the Eureka Quick Up vacuum product system using the object-oriented LCA methodology proposed in this research.

6.2.1. Goal and Scope Definition

When following the ISO 14040 and 14044 standards the first step in completing an LCA is the goal and scope definition. The goal and scope traditionally describes the purpose of the LCA study, the system boundaries, and the functional unit. In this case study, the goal and scope will describe the purpose of the LCA study and then go through the steps of the proposed methodology in order to define the LCA system boundaries, functional system boundaries, and Cumulative Damage Function. The product system life span that is calculated through this method is essential an updatable replacement for the traditionally static functional unit and product life expectancy. Therefore, the goal and scope components as outlined by the ISO standards are inherently built into the proposed framework, but are carried out in a more abstract functional manner than the traditional method. By defining the scope and system boundaries in terms of the product system function, the application can be adapted to assess any technology that performs the defined function. When following the traditional guidance on goal and scope definition, the assessment immediately becomes technology specific such that a new assessment and analysis is needed to evaluate an alternative solution.

This complete case study entails conducting and comparing the methods and results of two LCAs. The goal of the first LCA is to implement the refined object-oriented LCA methodology proposed in this research and to demonstrate the methodology's usability with current modeling software. The goal and scope phase here will proceed through the full set of object-oriented LCA steps. First, the system boundaries of the Eureka Quick Up Vacuum system must be defined in terms of the broader LCA context and the vacuum system function according to *Step 1 – System Definition*. The system boundaries in terms of the broader LCA context define what life cycle phases will be included in the assessment. Although the ISO standard does not mandate that all life cycle phases be included for the assessment to be considered a full LCA, for thoroughness, this assessment will be cradle-to-grave. Figure 8 shows the complete LCA system boundaries with the functional use phase boundary also shown to describe how the abstract functional definition of the product use fits into the broader LCA context. These two levels of system boundary definition provides the scope of the study and what life cycle phases will be analyzed in order to achieve the goal of the study.

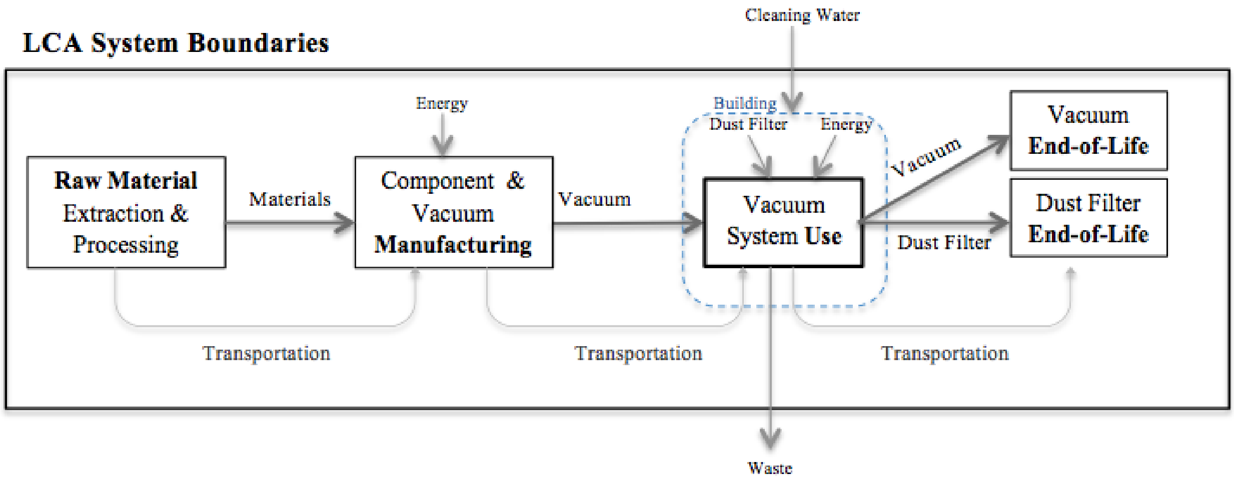

Figure 8: Eureka Quick Up 2-in-1 Vacuum LCA System Boundaries

Following *Step 1 – System Definition*, the functional use phase boundaries must be defined for the vacuum product system. This entails defining what the function of the system is, the function's corresponding material and energy inputs and outputs, interfacing systems, and enclosing system. As outlined in section 2.4.1., the function of a product system should be defined as an active verb-noun pair and must remain at a high level of abstraction as to ensure that it is solution independent and can consider a wide range of scenarios. Here, the Eureka Quick Up Vacuum is functionally defined as 'remove debris from surface'. Figure 9 shows the functional definition of the vacuum system and its corresponding attributes as needed for goal and scope definition. It is important to reiterate here that it is not essential that all inputs and outputs required for the functional transformation be defined. Rather, only those inputs and outputs that are common to all systems that perform the defined function. In this case study the only material input defined is 'surface w. debris' and the only energy input defined is 'kinetic energy'. Kinetic energy is defined because regardless of solution, the particle will move. The actual type of energy input is solution dependent. These inputs, while not comprehensive for the specific Eureka Quick Up Vacuum, are sufficient to define the inputs associated with the function 'remove debris from surface'.

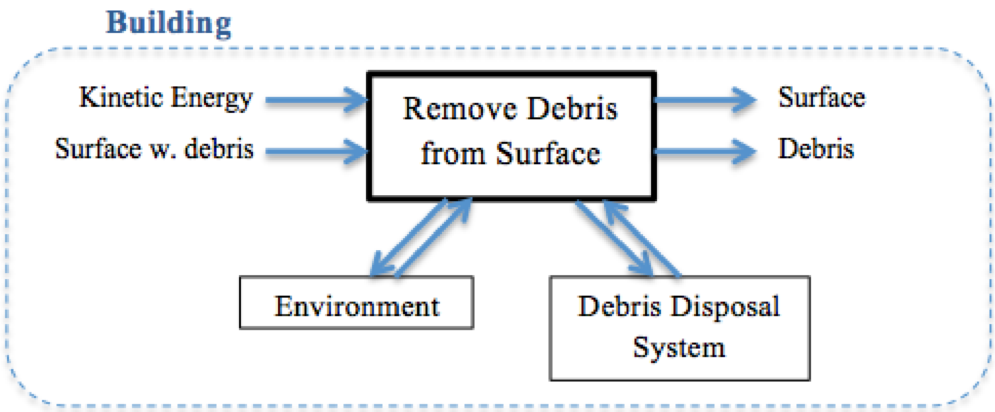

Figure 9: Functional Definition of Eureka Quick Up 2-in-1 Vacuum System

The box around the function 'remove debris from surface' represents the functional transformation that occurs when the function is carried out on the defined inputs. Therefore the outputs defined in this methodology are based on the corresponding inputs. The outputs in this case study are defined as 'surface' and 'debris' because the functional process separates the single input of 'surface w. debris' into two separate outputs. It is demonstrated in this example that the inputs and outputs defined by this methodology do not necessary show a balance of mass and energy, but inherently in the system there must be a conservation of mass and energy. This is shown in Figure 9 as 'kinetic energy' as an input, but there is not energy output because the kinetic energy is converted to some form of potential energy within the functional transformation space. The type of potential energy depends on the specific technology solution that is completing the 'remove debris from surface' function. The conservation of mass is shown more explicitly in this example because the outputs of 'surface' and 'debris' in combination with the mass associated with the 'debris disposal system' will equal the mass of the single 'surface w. debris' input. This brings attention to the critical role that the definition of the interfacing systems plays in the full definition of the functional use phase.

The interfacing systems represent those systems that interact directly with and affect the function of the primary system. The environment will always be an interfacing system to any product system because under any condition on this Earth there will be the atmospheric environmental conditions acting on the product system. After identifying the environment, the functions of the product system consumables must be identified as interfacing systems, where appropriate. It is important to reiterate once again that at this stage in the methodology all system definitions must remain technology independent and must be abstracted to the functional level. In this case study the interfacing systems identified are ‘environment’ and ‘debris disposal system’. The ‘debris disposal system’ was identified as an interfacing system in this case study because no matter what technology solution carries out the primary function there must by a system which collects the separated ‘debris’ output. The debris in this system is unwanted mass on the given surface that needs to be removed. Therefore is it a given that a disposal system is necessary because without a system to disposal of the debris it would remain on the surface.

After defining the primary system function, inputs, outputs, and interfacing systems, the final component of *Step 1 – System Definition* is to define the enclosing system of the functional use phase boundaries. Defining the enclosing system provides the context for which the product system is used, in this case study. The enclosing system also provides the LCA scope. The enclosing system defined in this study is ‘building’, which means that the product function of ‘remove debris from surface’ is completed within a standing structure with a roof. The scope of the study could be expanded by defining the enclosing system as ‘Earth’, in which case the context of where the product system could function would be anywhere on this planet in any circumstances. However, in this case study the context is limited to ‘building’ in order to maintain the relative simplicity of implementing the proposed methodology and ultimately achieving the research goal.

Overall, it is critical that *Step 1 – System Definition* is not rushed because the definition of the system components outlined above create the basis for which the rest of the study relies on. Best engineering judgment and practitioner expertise should go into all steps of this methodology and a sanity check should be completed after each step to ensure the best results. As a whole Figure 9 shows the functional use phase boundaries and within this context the use-parameters will be defined according to *Step 2a – 2d: Systematic Definition of Use-Parameters and Scaling Parameters.*

Following *Step 2a – 2d: Systematic Definition of Use Parameters and Scaling Parameters*, the complete set of use and scaling parameters will be defined for the Eureka Quick Up vacuum system in this LCA case study. The complete *Step 2* follows the same systems engineering perspective and thinking as *Step 1*. By ensuring that the same systems perspective is used throughout this methodology, each step is easily an extension of the last and proceeds seamlessly into the next. Here, *Step 2* is implemented in order to systematically define the scaling parameters that will ensure the accurate and complete modeling of the vacuum system use phase.

First, *Step 2a: Defining Product Scaling Parameters* is followed in order to define the product factors, which are the factors that describe the technical operating parameters and product system features of the Eureka Quick Up vacuum. This step entails completing a functional decomposition of the vacuum system, which is considered a well-established engineering tool that systematically determines all subsystems of a particular product (Umeda et al.,1990). Here the function of 'remove debris from surface' is decomposed down to the appropriate level. The appropriate level in this methodology is defined as the decomposition level at which the next level would need to assume technology solutions in order to complete for the specific product of interest. For this step of the use parameter definition a type of solution that achieves the primary function of 'remove debris from surface' must be identified. In this case the type of solution that is identified is a vacuum, however the specific technology by which the vacuum carries out its function is not assumed in this step. Other types of solutions that also 'remove debris from surface' would be a dry mop or broom and dustpan. Figure 10 shows the functional decomposition completed to the appropriate level for the purposes of this methodology step. The second level of decomposition is deemed as the appropriate level for this case study, however the appropriate level should be determined on a case-by-case basis. The third level of decomposition is shown in Figure 10 to confirm that in order to complete this level it requires specific solution assumptions. Therefore, this demonstrates that the second level of decomposition is the appropriate level to identify for further definition of the product scaling parameters in this case study.

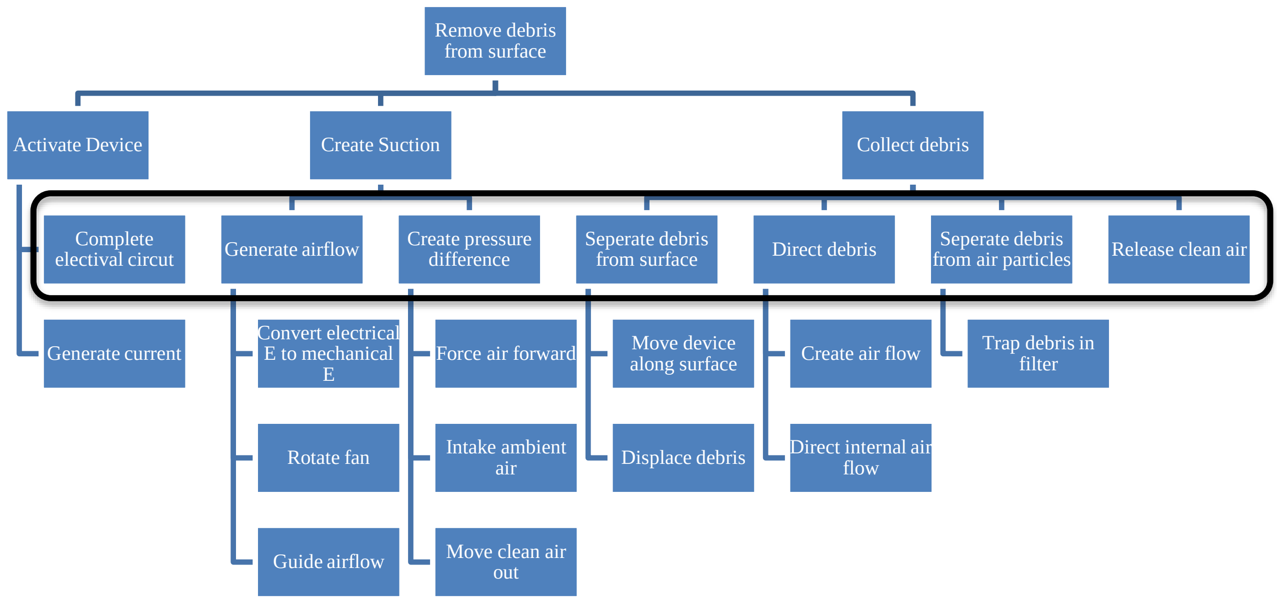

Figure 10: Functional Decomposition of Vacuum System

The identified subfunctions in Figure 10 are translated into use parameters using the best engineering judgment of the practitioner. The use parameters at this stage are also known as engineering metrics, which are quantifiable descriptors of the associate sub-function. The best way to determine the metrics are to ask how to quantify each sub-function identified; for example, how is ‘generate current’ quantified? While fundamental electrical principles dictate that current is measured in ampere’s that is not the appropriate engineering metric for this sub-function because amperes do not describe how current is generated. Current is the flow rate of electric charge, but this charge must come from a source of power. Therefore the appropriate engineering metric and use parameter for ‘generate current’ is ‘power generated’. This thought process is completed for all eight subfunctions identified in Figure 10 and Table 11 shows the mapping of these subfunctions to engineering metric or use parameter. The engineering metrics are technical aspects of the product system.

Through this process of following *Step 2a: Defining Product Scaling Parameters* for the ‘remove debris from surface’ system eight product use parameters are identified. These product use parameters will ultimately be converted, along with the situation use parameters, to unique scaling parameters, which are scaled all to the same unit.

Table 11: Mapping of 3rd Level Decomposition Sub-functions to Use Parameters

Subfunction	Product Use Parameter
Complete electrical circuit	Power generated
Generate current	
Generate airflow	Fan rotational speed
Create pressure difference	Static or water lift Airflow within vacuum
Separate debris from surface	Device movement
Direct debris	Airflow within vacuum
Separate debris from air particles	Particles collected
Release clean air	Air export speed

While functional decomposition is widely considered a well-established systems engineering tool, this methodology sheds light on the question as to whether or not there is one consistent way of completing the functional decomposition exercise. Since functional decomposition in this methodology is a critical step in defining the product use parameters, this is an important question to resolve. Furthermore, if there is not one way of completing functional decomposition, it is not certain whether different iterations of the decomposition for the same function will result in different product use parameters being defined. It is assumed that different iterations will result in the same product use parameters because the flow of material and energy attributes from the top function to lower sub-functions must be consistent between iterations in order for them to be correct functional decompositions. Different iterations may be structured or worded differently, but fundamentally it is hypothesized that all correctly executed functional decompositions for the same primary function will lead to the same results. In order to confirm that different iterations of decomposition for the same function will result in the same use parameters, three iterations of decomposition are compared. Figure 10 represents the first iteration of function decomposition completed for 'remove debris from surface', Figure 11 represents the second iteration, and Figure 12 represents the third iteration. In each of these figures, the appropriate level of decomposition needed to define product use parameters is highlighted. Next, these highlighted sub-functions are translated into engineering metrics or product use parameters for each iteration as shown in Table 12 and Table 13. The product use parameters generated from each of the three iterations of functional decomposition are then compared for consistency.

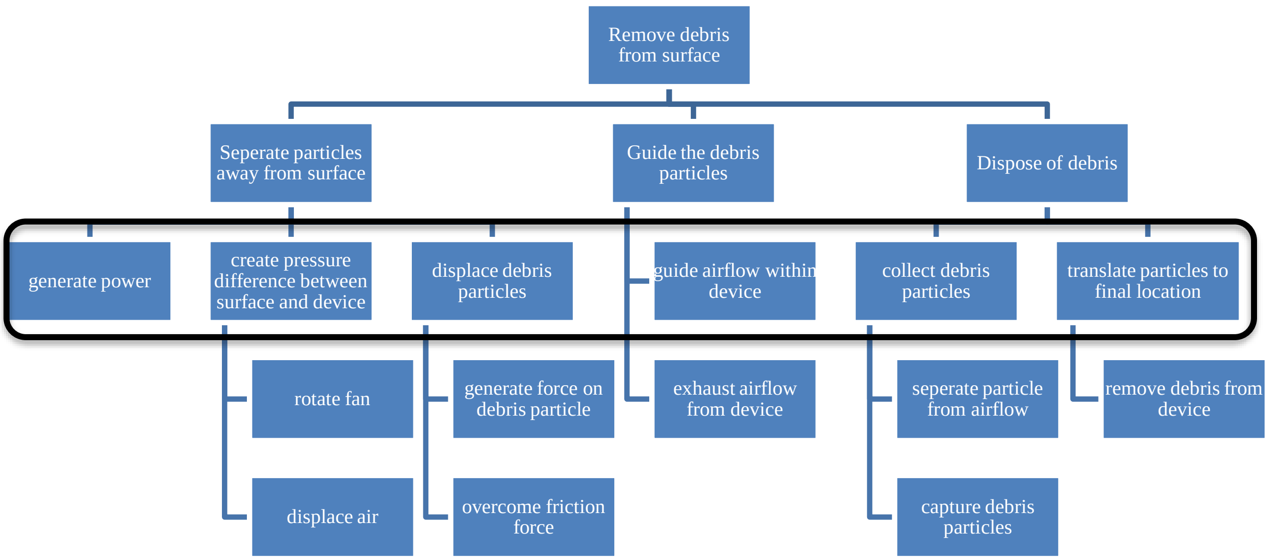

Figure 11: Second Iteration of 'Remove Debris from Surface' Functional Decomposition

Table 12: Second Iteration Mapping of 3rd Level Decomposition Sub-functions to Product Use Parameters

Sub-function	Product Use Parameter
Generate power	Power generated
Create pressure difference between surface and device	Static or water lift Fan rotational speed
Displace debris particles	Device movement
Guide airflow within device	Airflow within vacuum
Exhaust airflow from device	Air export speed
Collect debris particles	Particles collected
Translate particles to final location	Particles collected

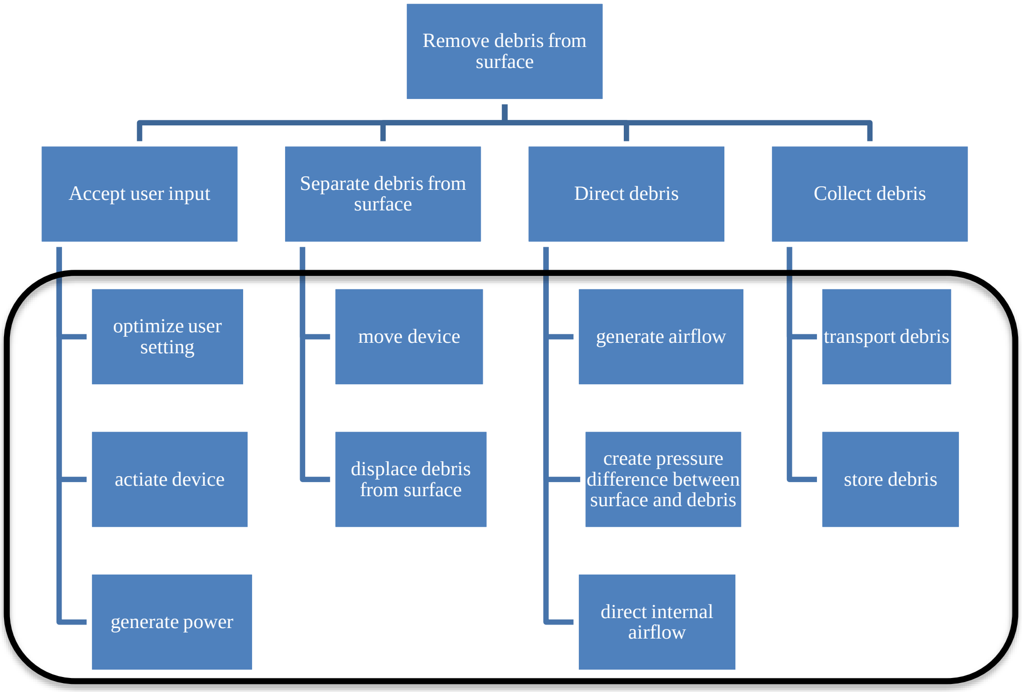

Figure 12: Third Iteration of 'Remove Debris from Surface' Functional Decomposition

Table 13: Third Iteration Mapping of 3rd Level Decomposition Sub-functions to Product Use Parameters

Subfunction	Product Use Parameter
Optimize user setting	Space between device and surface
Activate device	Power generated
Generate power	Power generated
Move device	Device movement
Displace debris from surface	Static or water lift Fan rotational speed
Generate airflow	Fan rotational speed
Create pressure difference between surface and debris	Static or water lift Fan rotational speed
Direct internal airflow	Airflow within vacuum
Transport debris	Airflow within vacuum Air export speed
Store debris	Particles collected

Table 14: Comparison of 3 Iterations of 'Remove Debris from Surface' Functional Decomposition Resulting Product Use Parameters

1st Iteration: Product Use Parameters	2nd Iteration: Product Use Parameters	3rd Iteration: Product Use Parameter	Comparison of Use Parameters Across Iterations
Power generated	Power generated	Power generated	Consistent across iterations
Static or water lift	Static or water lift	Static or water lift	Consistent across iterations
Device movement	Device movement	Device movement	Consistent across iterations
Airflow within vacuum	Airflow within vacuum	Airflow within vacuum	Consistent across iterations
Air export speed	Air export speed	Air export speed	Consistent across iterations
Particles collected	Particles collected	Particles collected	Consistent across iterations
Fan rotational speed	Fan rotational speed	Fan rotational speed	Consistent across iterations
		Space between device and surface	Variability across iterations

The side-by-side comparison of product use parameters identified from the three iterations of functional decomposition of the 'remove debris from surface' function allows for further analysis of functional decomposition variability. Different individuals, with systems engineering and functional decomposition experience, generated each of the three iterations of functional decomposition independently from one another. Each functional decomposition iteration of the same initial function resulted in some subfunctions with different word choice and altogether different organization of these subfunctions. This analysis is to determine if these differences in functional decomposition effect the generation of different product use parameters in this methodology or if the similarities of content between the iterations result in consisted use parameter definition, as expected. The side-by-side comparison of use parameters in Table 14 shows the unique product use parameters defined from each iteration of functional decomposition. For example, the 3rd iteration of functional decomposition defines 'power generated' twice as a use parameters based off of the subfunctions of 'activate device' and 'generate power', but in Table 14 'power generated' is only listed once for comparison to eliminate redundancies. The 1st functional decomposition iteration has 7 unique product use parameters, the 2nd iteration has 7 unique product use parameters, and the 3rd iteration has 8 unique product use parameters.

The comparison of unique product use parameters across the 3 iterations of functional decomposition indicates that 7 product use parameters are common across all 3 iterations, while 1 product use parameter is only determined from the 3rd iteration. The 1 product use parameter that is only determined from the 3rd iteration of functional decomposition is 'Space between device and surface'. The reasons for this variability in use parameter definition across iterations could be because iteration 1 and 2 fail to fully identify all parameters, iteration 3 inaccurately identifies a use parameter, and/or iteration 1 and 2 capture the quantitative impacts of the variable use parameter through another use parameter.

Through deductive reasoning it is determined that the use parameter 'space between device and surface' is only identified in the 3rd iteration of functional decomposition because the 3rd iteration inaccurately identify this as a product use parameter and because the 1st and 2nd iterations capture the same quantitative impacts through other use parameters. Specifically, the impacts associated with the 'space between device and surface' are captured under 'power generated' and 'particles collected'. This is determined because logically if there are two cases where the power generated is kept constant, but the distance between the surface and the device changes, the number of particles will also change accordingly. If power is constant, but the device is farther away from the surface than there will be less suction to remove the heavier particles from the surface leading to fewer total particles collected. Therefore, the impacts of the use parameters 'power generated' and 'particles collected' correlate and capture the impacts associated with 'space between device and surface".

It is also determined that the use parameter 'space between device and surface' is only identified in the 3rd iteration of functional decomposition due to this iteration inaccurately identifying this as a product use parameter. 'Space between device and surface' should be a system damage multiplier rather than a product use parameter. This is because the space between the device and surface is ultimately determined by the user input. For some products designed to remove debris from a surface there are settings such as 'floor' and 'carpet', which is feature that allows the user to optimize the system for a specific use scenario. For products that do not have this optimization feature, there are other user input factors, such as force on device, which can affect the space between the device and surface. Since 'space between device and surface' is clearly a factor determined by the user input, which can affect how efficient the product system is at removing debris from a surface, it is clearly a damage multiplier. There will be more discussion on determining damage multipliers later in this section.

The next, *Step 2b: Defining Situational Scaling Parameters* is followed in order to continue systematically defining the entire set of use and scaling parameters for the ‘remove debris from surface’ system. The situational use parameters are defined based on the interfacing systems, which are ‘debris disposal system’ and ‘environment’ in this case study. The factors of these two interfacing systems that affect the ‘remove debris from surface’ system as expressed in a quantifiable way, will be the use parameters. Not all factors of these interfacing systems will be situational use parameters. For example, a factor of the ‘environment’ is the color of the surface, but this would not be identified as a situational use parameter because this is not a factor that would affect the functionality of the primary system.

As outlined in the methodology, the ‘environment’ will always be an interfacing system but the factors of the ‘environment’ that affect the primary system of interest are not always the same from study to study. In this case study the factors of the ‘environment’ that effect the ‘remove debris from surface’ system include those quantifiable attributes of the ‘environment’ that relate to the surface and the debris. These include surface type, debris type, surface are, and debris quantity. Next, the aspects of the task performed under the primary system that are quantifiable must be defined to completely capture the situational parameters. These aspects of the task in this case study are defined based on the interfacing system, ‘debris disposal system’. Identifying the task factors and the associated use parameters of this interfacing system enables the LCA model to capture the impact of the consumables. Although it has been reiterated multiple times throughout this study that at this stage a specific technology solution should not be assumed, it will be pointed out specifically at this step again. It is restated here because without careful consideration, it could be easy for the practitioner to start referring to consumables in a solution specific way. However, just as when defining the use parameters of the vacuum system as a whole, the use parameters related to consumables must also remain solution independent. In this case study the factors of the ‘debris disposal system’ that affect the ‘remove debris from surface’ system include the frequency of replacing and cleaning the disposal system. These two situational parameters capture the consumer dependent behavior of how consumables are used. This sheds light on the case where if the user does not adequately maintain consumables it could start to degrade the functionality of the primary system function.

If, for explanatory sake, a traditional household suction vacuum is considered, the dust container must be emptied and the filter must be cleaned on a regular basis otherwise the ability for the vacuum to remove debris from a surface starts to decline. However, this methodology assumes that each use parameter is independent of one another. The consideration of interdependence of use parameters, as in the example of extended time between dust container and filter cleaning effecting primary functionality, is outside the scope of this study methodology. Therefore, in this study it is assumed that the user behavior is ideal such that interdependence of use parameters does not need consideration.

Table 15 shows the full list situational use parameters and from which interfacing system they were defined. It is clear through the definition of these situational parameters that this step takes careful consideration throughout the process and a final sanity check to ensure completeness.

Table 15: Situational use parameters and the associated interfacing system of the 'remove debris from surface' system

Interfacing System	Situational Use Parameter
Environment	Surface type
	Debris type
	Surface area
	Debris quantity
Debris disposal system	Disposal system replacement frequency
	Disposal system cleaning frequency

Next, *Step 2c: Defining Human Scaling Parameters* is followed in order to continue systematically defining the entire set of use and scaling parameters for the ‘remove debris from surface’ system. As highlighted in the proposed methodology, the human scaling parameters defined by this method are the aspects associated with the use phase in a traditional LCA such as time and frequency of product use. These aspects in a traditional LCA are the most variable and are the fundamental initial motivation for developing this present object-oriented methodology. Human scaling parameters in this case study are aspects of the user and the user interactions with the ‘remove debris from surface’ system. According to the methodology it is important to consider aspects of the task specification and operational procedures. Just as with *Step 2b: Defining Situational Scaling Parameters,* the present step is based largely on guided brainstorming instead of a structured method. Therefore, as in *Step 2b,* it is important that careful consideration is used throughout the definition of human parameters and a final sanity check is done to ensure completeness.

In this case study, when considering the user and user interactions with ‘remove debris from surface’ product system in the context of task specification and operational procedures, the scaling parameters to consider are related to time, frequency, and efficiency or damage. The human scaling parameters for this case study are therefore ‘time in use’, ‘frequency of use’, and ‘efficiency during use’. Through the implementation of this step to a case study here it becomes clear that time, frequency, and efficiency should always be considered when defining the human use parameters for any system. This is because these are the three fundamental aspects that the user afflicts on the system during their use. It is postulated that every system will have these same three human scaling parameters, plus any additional aspects that may be unique to the specific system of interest. While these three human scaling parameters should be defined for any study the unit and value to which they are scaled will be different for each unique system.

The next step in completing the goal and scope definition under the context of the object-oriented LCA methodology is *Step 2d: Converting Use Parameters to Scaling Parameters*, which by following this step determines the scaling parameters associated with the defined use parameters. The full set of product, situational, and human use parameters convert to scaling parameters in order to define the Cumulative Damage Function, ensure a fully defined use phase in this LCA model, and enable a model that can be scaled to any use scenario. The conversion to scaling parameters ensures that there is no double counting of use phase impacts, that all aspects of the use phase are captured, and that the parameters can be scaled to a common unit. The discretion of the practitioner is used in order to convert the use parameters to scaling parameters. Things that must be thoughtfully considered is if multiple use parameters correlate to one scaling parameter, if a parameter should be considered a damage multiplier rather than a variable, what unit is appropriate, and the tense of the word choice. It is also important to note that since this case study is meant to demonstrate the application of the proposed methodology on an LCA study more than one product use parameter can be converted to a single scaling parameter. Table 16 shows the full list of product, situational, and human use parameters defined according to the systematic methodology, the use parameters converted to scaling parameters, and the associated scaling unit.

Table 16: Use Parameter Conversation to Scaling Parameters and Scaling Unit Definition

Use Parameter	Scaling Parameter
Product Parameters (unit: watt)	
Power generated	Power to remove debris
Fan rotational speed	
Static or water lift	
Airflow within vacuum	
Air export speed	
Device movement	Power to move device
Particles collected	*
Situational Parameters (unit: 0.5 mm debris removed)	
Surface type	Debris on high pile carpet
	Debris on low pile carpet
	Debris on hardwood floor
Surface area	**
Debris type	Large debris particles (1 mm) [1]
	Medium debris particles (0.5 mm) [1]
	Small debris particles (0.001 mm) [1]
Debris quantity	**
Disposal system replacement frequency	Debris collected before system is replaced
Disposal system cleaning frequency	Debris collected before system is cleaned
Human Parameters	
Time in use	Time in use
Frequency of use	Frequency of use
Efficiency during use	Efficiency during use

* this parameter is captured and categorized as a situational scaling parameter

** this use parameter is captured through other identified scaling parameters

[1] Mølhave, L., T. Schneider, S. K. Kjaergaard, L. Larsen, Svend Norn, and O. Jørgensen. "House dust in seven Danish offices." Atmospheric Environment 34, no. 28 (2000): 4767-4779.

As previously mentioned, with the conversion of use parameters to scaling parameters, it is important to consider if any parameter is a damage multiplier rather than a true use or scaling parameter. In this case, it is clear that all human parameters and the last two situational scaling parameters defined in Table 16 are damage multipliers rather than scaling parameters. To reiterate from the methodology, a damage multiplier is an element of the system that quantitatively describes the state or quality of the function being performed. Use and scaling parameters on the other hand quantitatively describe a characteristic of the physical product. Table 17 shows the final list of scaling parameters for the function 'remove debris from surface', the quantification of the constant factor associated with each scaling parameter, and each parameter value for the use scenario. In practice, the use scenario parameter values should be quantified using situational testing. Table 18 shows the identification and quantification of time factors, which will be used to calculate use phase energy consumption and will be used to determine time damage multipliers.

Table 17: Quantification of Scaling Factors and Use Scenario Parameters

Scaling Parameter	Parameter	Constant Scaling Factor	Use Scenario Parameter Value
Reference flow: Kinetic Energy **Unit:** kilowatts			
Power to remove debris	y_1	1	0.072
Power to move device	y_2	1	0
Reference flow: Debris **Unit:** 0.5 mm debris removed			
Large debris particles (1 mm) on high pile carpet (3/4	x_1	2	40
Large debris particles (1 mm) on low pile carpet (1/4 inch)	x_2	0.6	26
Large debris particles (1 mm) on hardwood floor (0 inch)	x_3	0.1	0
Medium debris particles (0.5 mm) on high pile carpet (3/4	x_4	4	85
Medium debris particles (0.5 mm) on low pile carpet (1/4	x_5	1.3	100
Medium debris particles (0.5 mm) on hardwood floor (0	x_6	0.2	0
Small debris particles (0.01 mm) on high pile carpet (3/4	x_7	200	300
Small debris particles (0.01 mm) on low pile carpet (1/4	x_8	66	110
Small debris particles (0.01 mm) on hardwood (0 inch)	x_9	4	0

Table 18: Quantification of Time Factors

Time Factor	Parameter	Use Scenario Parameter Value
Time in use removing debris	t_1	1200 seconds
Time moving device (not removing debris)	t_2	0 seconds

The scaling factor constants identified in this study are defined based on best judgment in order to demonstrate the usability of this methodology. However, when implementing this methodology for actual product design purposes or when conducting a full LCA study, the scaling factor constants should be identified through product testing and known values to ensure reliable results. In addition, the use scenario parameter values in this study are defined based on a hypothetical use scenario. When using this methodology for product design a hypothetical use scenario can be used that reflects standard customer use practices, but when using this methodology for a full LCA study a specific use scenario should be used that reflects the actual customer behavior that the practitioner is assessing.

Table 19 identifies the system damage multipliers and quantifies each factor's range, the total range, each factor's value in this case study use scenario, and the total damage multiplier in this case study use scenario based on best judgment. Just as with the quantification of scaling factor constants, when implementing this methodology for actual product design or full LCA purposes, the damage multiplier values should be identified through testing to ensure the most reliable results. In addition, the use scenario damage values for each factor in this case study are defined based on a hypothetical use scenario. The total damage multiplier is the product of each individual damage multiplier value and in this case study use scenario the total value is 2.6 in a potential range of 1-12.

Table 19: Quantification of Damage Multiplier Range and Use Scenario Values

Damage Multiplier	Parameter	Use Scenario Damage Multiplier Range	Use Scenario Damage Value
Damage of time removing debris	z_1	1 – 10 (only in use for time when debris is on floor – in use after all debris has been removed)	1.6
Damage of time moving device (not removing debris)	z_2	1 – 10 (only moving device when removing debris – moving device when not removing any debris)	1
Area overlap with each device pass	z_3	1– 2 (no overlap - complete overlap)	1.3
Distance between device and surface	z_4	1 or 1.5 (optimal distance – non optimal distance; i.e. hardwood setting on high pile carpet)	1
Debris collected before debris removal system is replaced	z_5	1 or 2 (replaced at time before function effectiveness is degraded – replaced after function effectiveness is degraded)	2
Debris collected before debris removal system is cleaned	z_6	1 or 2 (cleaned at time before function effectiveness is degraded – cleaned after function effectiveness is degraded)	1
Total Damage Factor (*z*)	z	1 – 1,200	4.16

The damage multiplier value is always unit-less because it reflects the quality or state by which the use parameters function is performed. The optimal total damage multiplier value for any system is always 1 because this reflects a use scenario where the use parameters are able to perform to their full function and no additional environmental impacts are incurred in the use phase due to user inefficiencies. The higher the total damage multiplier value the more environmental impacts are associated with the use phase because user inefficiencies cause the system to perform sub-optimally. It is postulated that the more human input needed for a system to function, the greater the total damage multiplier value will likely be for that system. The use of relatively arbitrary damage multiplier values in this case study is merely meant to demonstrate the usability of this step as an integrated part of the full goal and scope methodology and show how the efficiency of product use could have a large impact on the overall environmental impacts of the system.

Now that all scaling parameters and damage multipliers for the Eureka Quick-Up 2-in-1 product system have been identified, the use scenario identified in this case study is input into the Cumulative Damage Function as seen in Equation 8. To reiterate from the methodology, the Cumulative Damage Function models the use phase of the product lifecycle as a function of the technical product attributes, interfacing system attributes, and user efficiency. In order for this equation to apply to a different class of products that perform the function 'remove debris from surface' the product parameters x_1 and x_2 would need to be substituted with the appropriate product parameters. While the product parameters for a different product may be the same as identified for the household vacuum in this case study, the methodology must be followed for every system of interest in order to ensure reliability of results.

Equation 8

$$\begin{aligned}\begin{matrix} Cumulative \\ Damage\ Function \end{matrix} &= z\,(2x_1 + 0.6x_2 + 0.1x_3 + 4x_4 + 1.3x_5 + 0.2x_6 + 200x_7 + 66x_8 + 4x_9) \\ &= 4.16\,(2(40) + 0.6(26) + 0.1(0) + 4(85) + 1.3(100) + 0.2(0) + 200(300) \\ &\qquad + 66(110) + 4(0)) \\ &= 2.82 \times 10^5\ medium\ (0.5\ mm) debris\ particles\ removed\end{aligned}$$

Next, the Cumulative Damage Function is input into the System Impact equation as shown in Equation 9. The System Impact equation determines the percentage of total useful life that the specific use case makes up. The percentage determined from the System Impact equation is the percentage of the product system that will be modeled. The numerator of this equation is the Cumulative Damage Function while the denominator is the total useful life of the product. The total useful life of the product is determined based on best judgment in this case study because systematic definition of this component is out of the scope of this study. More research is needed around determining a method of quantifying the total useful life of a product.

Equation 9

$$\begin{matrix} System \\ Impact\ (\%) \end{matrix} = \frac{z\left(2x_1 + 0.6x_2 + 0.1x_3 + 4x_4 + 1.3x_5 + 0.2x_6 + 200x_7 + 66x_8 + 4x_9\right)}{Product\ System\ Life\ Span} \times 100$$

$$= \frac{2.82 \times 10^5\ medium\ (0.5\ mm) debris\ particles\ removed}{4.5 \times 10^9\ medium\ (0.5\ mm) debris\ particles\ removed} \times 100$$

$$= 0.00627\ \%$$

The next step in following the proposed goal and scope methodology is *Step 3: Quantifying Use Phase Energy*. Equation 10 quantifies the use phase energy for the use scenario defined in Table 17 and Table 18.

Equation 10

$$Use\ Energy\ (kWh) = (y_1 \cdot t_1) + (y_2 \cdot t_2)$$

$$= \left(0.072\ kW \cdot \frac{1200\ s}{3600\ s}\right) + \left(0\ kW \cdot \frac{0\ s}{3600\ s}\right)$$

$$= 0.024\ kWh$$

As the proposed methodology outlined in Section 5 is applied to this case study it has shed light on some aspects of the method that need more attention. Specifically there are three aspects that need added guidance in this goal and scope method including how to appropriately model product consumables, how to appropriately model product transportation, and the distinction between applying this methodology to an LCA study versus product development.

In a traditionally conducted LCA in which there is a static functional unit, consumables are treated as a separate life cycle at a quantity appropriately proportional to the functional unit. Consumables in this methodology should be treated the same in that they are modeled as a separate life cycle and the quantity is appropriately proportional to the system impact. However, in this methodology application the consumable quantity should be input into the model as a calculated parameter so that it will update easily and quickly as the use scenario parameters are updated. By inputting the consumable quantity as a calculated parameter in SimaPro the value will update automatically, rather than when input as an integer the practitioner has to manually recalculate the consumable quantity for every new use scenario. The consumable parameter equation will need to be developed and implemented on a case-to-case basis depending on the product system of interest. However, generally the consumable quantity will be a function of the known quantity of consumables used for a given useful life the use scenario cumulative damage function value. The consumable used in the Eureka Quick Up 2-in-1 vacuum system is the dust filter and Equation 11 shows the equation used to calculate the appropriate number of dust filters consumed in this case study use scenario.

Equation 11

$$\begin{matrix} \mathit{Dust\ Filters} \\ \mathit{Consumed} \end{matrix} = \frac{1\ \mathit{dust\ filter}}{2.25\ \times 10^{9}\ \frac{\mathit{medium}\ (0.5mm)}{\mathit{debris\ particles\ removed}}} \cdot 2.82\ \times\ 10^{5}\ \frac{\mathit{medium}\ (0.5mm)}{\mathit{debris\ particles\ removed}}$$

$$= .000125\ \mathit{dust\ filters}$$

The second aspect that needs some guidance in this goal and scope methodology is how to appropriately model the transportation of the product and consumables. Just as with the guidance around modeling consumables in this object-oriented method, transportation modeling should be handled using the same guidelines as when modeling transportation in a traditional LCA. This entails multiplying the weight of the product that is consumed in the defined use scenario by the distance traveled. However, in the application of modeling transportation in this object-oriented methodology the transportation weight-distance values should be entered as calculated parameters instead of integers. This is so that as any use scenario is input as input parameters in SimaPro the associated transportation values will update automatically and the practitioner will not have to manually recalculate these values for each use scenario modeled. For the present case study of the Eureka Quick Up 2-in-1 Vacuum, Table 20 shows the corresponding transportation distances for the vacuum product and dust filter consumable and Equation 12 and Equation 13 show how the transportation impact should be modeled as a calculated parameter for one leg of the product and consumable distribution.

Table 20: Transportation for Eureka Quick Up 2-in-1 Vacuum and Dust Filter

Location Origin	Location Destination	Distance Traveled (km)	Transport Type
Eureka Quick Up 2-in-1 Vacuum			
Ningbo City, China – Manufacturing Plant	Grand Harbour, China – Distribution Port	30 km	Truck
Grand Harbour, China – Distribution Port	Long Beach, CA, USA – Distribution Port	10,600 km	Freight Ship
Long Beach, CA, USA – Distribution Port	Fairburn, GA, USA – Distribution Center	3,550 km	Train
Fairburn, GA, USA – Distribution Center	Rochester, NY, USA – Retail Store	1,577 km	Truck
Eureka Quick Up Dust Filter			
Long Beach, CA, USA – Domesticated Manufacturing Plant	Fairburn, GA, USA – Distribution Center	3,550 km	Truck
Fairburn, GA, USA – Distribution Center	Rochester, NY, USA – Retail Store	1,577 km	Truck

Equation 12

$$\begin{matrix} Product\ Transportation \\ Process\ (kgkm) \end{matrix} = (Product\ Weight\ (kg) * System\ Impact) * Distance\ (km)$$

Equation 13

$$\begin{matrix} Consumable\ Transportation \\ Process\ (kgkm) \end{matrix} = \begin{pmatrix} Consumable & * & Consumable \\ Weight\ (kg) & & Consumed \end{pmatrix} * \ Distance\ (km)$$

As mentioned, a goal of implemented the updated proposed methodology on this case study is to determine any areas of this methodology or modeling application that need more development. The third aspect that was identified as needing more attention is the need to distinguish, at a high level, between LCA and product development application of this goal and scope methodology. The case study presented in this work is purely an LCA application in that the methodology is applied to a preexisting product system to determine its environmental impacts for a specific use scenario. This means that the steps of this methodology were applied at the product system level and all product use parameters are rolled into two distinct scaling parameters.

However, when this object-oriented methodology is applied during product development the methodology steps should be applied to each sub-function and each product use parameter must remain distinct. This enables each sub-function to have its own set of input and output flows, use parameters, and scaling parameters for input into its own sub-functional level LCA. By extension, if all sub-function level LCAs are modeled together the results will be the same as applying this methodology and modeling the full product system level LCA. The advantage of applying this methodology at the sub-function level for product development is that it enables a sub-function to be easily interchanged with a different technology solution that performs the same sub-function. This creates an environmental product development concept generation tool in which an engineer can put together these building blocks of sub-functions to easily develop a full product system and determine the environmental impacts. In addition, the product development engineer can interchange different technologies that perform the same sub-function in order to determine which alternative is more environmental beneficial. While often times during product development a full product bill of materials is not available, this methodology allows engineers to plug-and-play, so to speak, with preexisting sub-functional level components. The full implementation of the proposed methodology to a product development application can be seen in the Masters Thesis work by Shantanu Avinash Gadre, which was developed concurrently to this research.

This culminates the implementation of the goal and scope definition according to the proposed LCA methodology developed in this research. The next step is to implement this case study into the environmental LCA modeling software, SimaPro. The case study is modeled in SimaPro in order to demonstrate the practical application in the LCA modeling software. The quantitative goal and scope definition and outlined in Table 17-19 translate into SimaPro as input parameters and calculated parameters as shown in Figure 13 and Figure 14. By implementing the proposed methodology using parameters instead of process integers it enables a model that can be easily updated with any use scenario without the practitioner having to manually remodel and recalculate every factor.

Input parameters

Name	Value	Distribution	SD^2 or 2*SD	Min	Max	Hide	Comment
t1	1200	Undefined					time in use removing debris (seconds)
t2	0	Undefined					time moving device (seconds)
x1	40	Undefined					large debris particles on high pile carpet (3/4 inch)
x2	26	Undefined					large debris particles on low pile carpet (1/4 inch)
x3	0	Undefined					large debris particles on hardwood floor (0 inch)
x4	85	Undefined					medium debris particles on high pile carpet (3/4 inch)
x5	100	Undefined					medium debris particles on low pile carpet (1/4 inch)
x6	0	Undefined					medium debris particles on hardwood floor (0 inch)
x7	300	Undefined					small debris particles on high pile carpet (3/4 inch)
x8	110	Undefined					small debris particles on low pile carpet (1/4 inch)
x9	0	Undefined					small debris particles on hardwood floor (0 inch)
y1	0.072	Undefined					power to remove debris/use power (kW)
y2	0	Undefined					power to move device (kW)
z1	1.6	Undefined					efficiency of time removing debris (1-10)
z2	1	Undefined					efficiency of time moving device (1-10)
z3	1.3	Undefined					area overlap with each device pass (range: 1-2)
z4	1	Undefined					distance between device and surface (range: 1 or 1.5)
z5	2	Undefined					debris collected before debris removal system replaced (range: 1 or 2)
z6	1	Undefined					debris collected before debris removal system cleaned (range: 1 or 2)
TotalWeight_Vacuum	2.38	Undefined					kg
TotalWeight_DustFilter	0.27	Undefined					kg
LifeSpan_debrisremoved_Vacuum	4500000000	Undefined					medium debris particles equivalent removed
LifeSpan_debrisremoved_DustFilte	2250000000	Undefined					medium debris particles equivalent removed
Distance_Mfg_Port	30	Undefined					km
Distance_Port_Port	10600	Undefined					km
Distance_Port_Distribution	3550	Undefined					km
Distance_Distribution_Retail	1577	Undefined					km

Figure 13: Vacuum Case Study Use Scenario Input Parameters

Calculated parameters

Name	Expression	Comment
TotalEfficiencyFactor_Vacuum	z1*z2*z3*z4*z5*z6 = 4.16	unitless
UseEnergy_Vacuum	(y1)*(t1/3600) = 0.024	kWh
CDF_debrisremoved_Vacuum	TotalEfficiencyFactor_Vacuum*(x1*2+x2*0.6+x3*0.1+x4*4+x5*1.3+x6*0.2+x7*200+x8*66+x9*4) = 2.82E5	medium debris particles equivalent
SystemImpact	CDF_debrisremoved_Vacuum/LifeSpan_debrisremoved_Vacuum = 6.27E-5	
DustFiltersConsumed	CDF_debrisremoved_Vacuum/LifeSpan_debrisremoved_Dustfilter = 0.000125	
UseCaseWeight_Vacuum	TotalWeight_Vacuum*SystemImpact = 0.000149	kg
UseCaseWeight_DustFilter	TotalWeight_DustFilter*DustFiltersConsumed = 3.39E-5	kg
TransportVacuum_Mfg_Port	UseCaseWeight_Vacuum*Distance_Mfg_Port = 0.00448	kgkm
TransportVacuum_Port_Port	UseCaseWeight_Vacuum*Distance_Port_Port = 1.58	kgkm
TransportVacuum_Port_Distribution	UseCaseWeight_Vacuum*Distance_Port_Distribution = 0.53	kgkm
TransportVacuum_Distribution_Retail	UseCaseWeight_Vacuum*Distance_Distribution_Retail = 0.235	kgkm
TransportDustFilter_Mfg_Distribution	UseCaseWeight_DustFilter*Distance_Port_Distribution = 0.12	kgkm
TransportDustFilter_Distribution_Retail	UseCaseWeight_DustFilter*Distance_Distribution_Retail = 0.0534	kgkm
UseCaseProductionEnergy_Vacuum	0.259*UseCaseWeight_Vacuum = 3.87E-5	kWh (0.259 kWh/kg)
UseCaseProductionEnergy_DustFilter	0.259*UseCaseWeight_DustFilter = 8.77E-6	kWh (0.259 kWh/kg)

Figure 14: Vacuum Case Study Use Scenario Calculated Parameters

This completes the implementation of the proposed functional based goal and scope methodology and therefore also concludes the LCA goal and scope phase for this case study. Next, in accordance with following the standard measures of completing an LCA study, the Life Cycle Inventory (LCI) must be completed.

6.2.2. Life Cycle Inventory and Impact Assessment

Inventory data for the Eureka Quick Up 2-in-1 Vacuum Cleaner is detailed in Table 21 including the product component based bill of materials and associated data source. It is important for the inventory assessment data be primarily organized at the component level rather than the material level in order for this methodology to extend itself to an object oriented function based method for product development. Note that the product use life cycle stage is not included in Table 21 because product use is fully captured by the goal and scope methodology followed in section 6.2.1. In a traditionally executed life cycle assessment the inventory analysis would have a line items for the electricity and consumables associated with product use however these system factors are also defined in the goal and scope phase methodology in section 6.2.1. All background data for product inventory data was sourced from the Ecoinvent v2.2 database.

Table 21: Life Cycle Inventory Data for Eureka Quick Up 2-in-1 Vacuum Cleaner

Life cycle stage	Value	Data Source
Product – Eureka Quick Up 2-in-1 Vacuum Cleaner		
Handle		
Material		
Polycarbonate	29.9 g	Own measurement
Polystyrene	29.9 g	Own measurement
Steel	6.4 g	Own measurement
Aluminum	117.0 g	Own measurement
ABS	4.5 g	Own measurement
Production		
Injection molding	64.4 g	Own measurement
Average steel product manufacturing	6.4 g	Own measurement
Average aluminum product manufacturing	117.0 g	Own measurement
Transportation		Industry Data
Upper Vacuum Casing		
Material		
ABS	621.4 g	Own measurement

Table continues on next page

Table continued from previous page

Steel	10.0 g	Own measurement
Production		
Injection molding	621.4 g	Own measurement
Average steel product manufacturing	10.0 g	Own measurement
Transportation		Industry Data
Lower Vacuum Casing		
Material		
ABS	259.0 g	Own measurement
Steel	10.7 g	Own measurement
Production		
Injection molding	259.0 g	Own measurement
Average steel product manufacturing	10.7 g	Own measurement
Transportation		Industry Data
Bristle Roller		
Material		
ABS	3.6 g	Own measurement
Foam ABS	52.6 g	Own measurement
Nylon	0.45 g	Own measurement
Production		
Injection molding	3.6 g	Own measurement
Thermoforming	0.45 g	Own measurement
Foaming, expanding	52.6 g	Own measurement
Transportation		Industry Data
Motor		
Material		
Motor	326.6 g	Own measurement
Roller Motor	81.6 g	Own measurement
Polycarbonate	68.0 g	Own measurement
ABS	0.23 g	Own measurement
Production		
Motor production	408.2 g	Own measurement
Thermoforming	0.23 g	Own measurement
Injection molding	68.0 g	Own measurement
Transportation		Industry Data
Power Switch		
Material		
Surface mounted circuit board, Pb free	7.5 g	Own measurement
ABS	2.8 g	Own measurement
Nylon 6-6	0.23 g	Own measurement
Production		
Circuit board production	1.3 cm^2	Own measurement
Injection molding	3.0 g	Own measurement
Transportation		Industry Data
Power Supply Cord		
Material		
Electrical wire	4.57 m	Own measurement
Production		
Electrical wire production	4.57 m	Own measurement
Transportation		Industry Data
Packaging		

Table continues on next page

Table continues from previous next

Material		
Paper	29.0 g	Own measurement
Low density polyethylene (LDPE)	19.1 g	Own measurement
Core board	44.5 g	Own measurement
ABS	8.4 g	Own measurement
Corrugated board	386.5 g	Own measurement
Production		
Plastic extrusion	19.1 g	Own measurement
Injection molding	8.4 g	Own measurement
Carton board production	386.5 g	Own measurement
Transportation		Industry Data
Production		
Manufacturing Energy	0.55 kWh	Own assumption
Transport		
Vacuum cleaner: China factory to Grand Harbour, China port	63.6 kgkm	Own assumption
Vacuum cleaner: Port (Grand Harbour) to Long Beach, CA USA port	22,472 kgkm	Own assumption
Vacuum cleaner: Port (Long Beach, CA) to Fairburn, GA distribution	7,526 kgkm	Own assumption
Vacuum cleaner: Distribution center (Fairburn, GA) to Rochester, NY retailer	3,343 kgkm	Own assumption
End of Life: Transport to waste treatment	106 kgkm	Own assumption
Consumable – Dust Filter		
Dust Filter		
Material		
ABS	263.5 g	Own measurement
Fabric Blend	1.8 g	Own measurement
Production		
Blow molding	259.5 g	Own measurement
Injection molding	4.1 g	Own measurement
Textile refinement	1.8 g	Own measurement
Transportation		Industry Data
Production		
Manufacturing Energy	0.069 kWh	Own assumption
Transport		
Dust filter: Domesticated factory (Long Beach, CA) to Fairburn, GA distribution	941.8 kgkm	Own assumption
Dust filter: Distribution center (Fairburn, GA) to Rochester, NY retailer	418.4 kgkm	Own assumption
End of Life: Transport to waste treatment	13.3 kgkm	Own assumption

While the goal and scope methodology used in this case study reduces the ambiguity in determining the environmental life cycle impacts there are some basic assumptions that still need to be made in order to fully define the product system. Table 22 defines the assumptions, by life cycle phase, made in order to complete this case study in addition to the explanation for making each assumption.

Table 22: Life Cycle Assumptions of the Eureka Quick Up 2-in-1 Vacuum Cleaner

Life Cycle Phase Assumption	**Rational/Explanation**
Raw Material	
All raw material transportation to manufacturing plan assumed to be industry average	Raw material plants are not known for this specific product or manufacturer so industry averages are used for transport distances from raw material facilities to manufacturing plant instead of assuming a value or defining outside the system boundaries. Industry averages are built into the Ecoinvent V 2.2 database for each material.
Vacuum handle was an unmarked part and assumed to be aluminum	Engineering judgment was used in defining the material of the vacuum handle. Aluminum was assumed because it is a low cost product, this part was light in weight, and aluminum is known to be a fairly low cost low weight material.
Roller bristles were an unmarked part and assumed to be Nylon 6	Engineering judgment was used in defining the material of the roller bristles. Nylon 6 was assumed because it is the commonly known plastic to be used in this type of application. Also Nylon 6 is known to be a relatively low cost material, which is logical for this low cost product.
Production Assumptions	
Vacuum cleaner is manufactured in a Chinese factory that is 30 km from the Grand Harbour Port	The exact location of Eureka's manufacturing factories is not known, but it is known that Eureka manufactures the Quick Up 2-in-1 Vacuum in China. The Grand Harbour Port is the largest port in China so using this port to model the transport was considered a conservative assumption. Furthermore, it was assumed that Eureka would have its manufacturing facility fairly close to the Grand Harbour Port in order to optimize their logistics so a distance of 30 km was assumed. This distance from the manufacturing facility to port is a moderate assumption.

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Dust filter consumable manufacturing is domesticated to a factory in Long Beach, CA	The exact location of Eureka's consumables manufacturing facility is not known, but it is known that the consumables are manufacturing in the United States when the end user is in the U.S. Assuming that the manufacturing facility is in Long Beach, California is a conservative assumption given that the end user in the case study use scenario is in New York because CA is the greatest distance away in the country.
Production energy assumed to be 0.259 kWh/kg	This assumption is taken from an electronics company study, which calculated the energy needed to complete the final assembly of a printer. It is noted that the source of this study is proprietary because it uses company specific data. This is considered a conservative assumption because the final assembly of a printer is most likely more complex than the final assembly of a household vacuum. However, because the vacuum does contain similar parts to a printer (i.e. circuit boards, motor, plastic casings) it is considered a reasonable assumption.
Use Assumptions	
North Eastern United States high voltage energy mix used during use phase	The end user in this case study is assumed to be in the north east of the United States, but the exact location is not specified in this case study so a North Eastern U.S. average energy mix is considered a valid assumption. The voltage level of the energy mix is also not specifically known so a high voltage mix is assumed in order to be conservative and ensure that impacts are not underestimated.
Transportation Assumptions	
Transportation route from China eastward to the United States to retail store	While the vacuum manufacturing facility is known to be in China it is not certain if the distribution of the vacuum takes a westward or eastward route to get to the United States. An eastward route is assumed in this case study because it would be the most efficient and logical route for Eureka to distribute to the United States.
End of Life Assumptions	

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At end of life the entire vacuum cleaner is disposed of via curbside solid waste pick up sent to landfill	The end of life of the vacuum cleaner can vary from one use scenario to another however it is assumed that in reality it will not vary because of tendencies of the common end user. The Eureka Quick Up 2-in-1 vacuum is not designed to be taken apart and is therefore difficult to take apart into separate material parts. Furthermore, since the product is not easy to take apart and the product as a whole is not recyclable it is valid to assume that the whole product is sent to the landfill at its end of life.
At end of life the entire dust filer consumable is disposed of via curbside solid waste pick up sent to landfill	The end of life of the dust filter consumable can vary from one use scenario to another however it is assumed that in reality it will not vary because of tendencies of the common end user. The Eureka vacuum dust filter is not designed to be taken apart and is therefore difficult to take apart into separate material parts. Furthermore, since the consumable is not easy to take apart and the consumable as a whole is not recyclable it is valid to assume that the whole consumable is sent to the landfill at its end of life.

Now that the goal and scope phase is complete and all modeling assumptions have been defined, the case study can be input into the SimaPro modeling software. The purpose of inputting the present case study into SimaPro is to demonstrate that the refined goal and scope methodology proposed in this research is a valid and finalized methodology for completing a full life cycle assessment. The purpose of the previous research on this methodology by Fumagalli (2012) was to demonstrate that the object-oriented goal and scope method was simply capable of being input into SimaPro and the method can be used to compare different technologies that provide the same function. In addition, the purpose of the additional work on this methodology by Shantanu Avinash Gadre, which was developed concurrently to this work, is to demonstrate the full usability of this methodology as applied to product development. Therefore there is no intent of implementing the present case study to either a comparable study or to a full product development study since both these applications have been demonstrated in other research works. As stated, the intent of the present case study is purely to implement the finalized object-oriented goal and scope methodology to demonstrate the full ease of usability and updatability of the method. Figure 15, Figure 16,

Figure 17, and Figure 18 show the modeling in SimaPro of the vacuum material assembly, vacuum transport, vacuum disposal, and dust filter life cycle, respectively. These 4 figures show the details behind 4 of the inputs to the Vacuum System Life Cycle as seen in Figure 19. In addition to these 4 inputs the use phase energy mix and manufacturing final assembly energy are input into Vacuum System Life Cycle in order to model the full product system in SimaPro. Another important modeling aspect to point out is that the 'Amount' specified for each 'Assembly' and 'Processes' line item in Figure 16-19 is a calculated parameter from Figure 14 instead of a static integer. This demonstrates how the goal and scope methodology proposed in this research is modeled in such a way that it is easy to update with each use scenario because once the SimaPro input parameters are changed the entire model automatically updates. If the 'Amount' specified in the SimaPro model are static integers, instead of input parameters, each and every 'Amount' in the model would need to be manually updated with each new use case. Figures 16-19 demonstrate this clear advantage of conducting an LCA using the present goal and scope methodology as opposed to the traditional approach. The 'Amount' of each of the vacuum assembly's in Figure 15 are static numbers because the materials of the product system remain constant and do not change under any use scenario.

Name	Status	Comment
Vacuum	None	

Materials/Assemblies	Amount	Unit
Bristle Roller	1	p
Handle	1	p
Motors	1	p
Lower Vacuum Casing	1	p
Power Supply Cord	1	p
Power Switch	1	p
Upper Vacuum Casing	1	p
Packaging	1	p

Figure 15: Vacuum Assembly Raw Material Modeling in SimaPro

Name	Status	Comment
Vacuum Transport	None	

Assembly	Amount	Unit	Distribution	SD2 or 2SD	Min	Max
	0		Undefined			

Processes	Amount	Unit
Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Rec, U	TransportVacuum_Mfg_Port = 0.00448	kgkm
Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Rec, U	TransportVacuum_Port_Port = 1.58	kgkm
Transport, freight train {US}| market for | Alloc Rec, U	TransportVacuum_Port_Distribution = 0.53	kgkm
Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Rec, U	TransportVacuum_Distribution_Retail = 0.235	kgkm

Figure 16: Vacuum Distribution Transportation Modeling in SimaPro

Name	Status	Comment
Dust Filter Life cycle	None	

Assembly	Amount	Unit	Distribution	SD2 or 2SD	Min
Dust Filter	DustFiltersConsumed = 0.000125	p			

Processes	Amount	Unit
Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Rec, U	TransportDustFilter_Mfg_Distribution = 0.12	kgkm
Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Rec, U	TransportDustFilter_Distribution_Retail = 0.0534	kgkm
Electricity, high voltage {CN}| market for | Alloc Rec, U	UseCaseProductionEnergy_DustFilter = 8.77E-6	kWh

Figure 17: Dust Filter Consumable Life Cycle Modeling in SimaPro

Name	Status	Comment
Vacuum Disposal	None	

Referring to assembly	Amount	Unit
Vacuum	SystemImpact = 6.27E-5	p

Processes	Amount
Add	

Waste scenarios	Percentage
Durable goods (waste scenario) {US}| treatment of waste | Alloc Rec, U	100 %

Figure 18: Vacuum Disposal Scenario Modeling in SimaPro

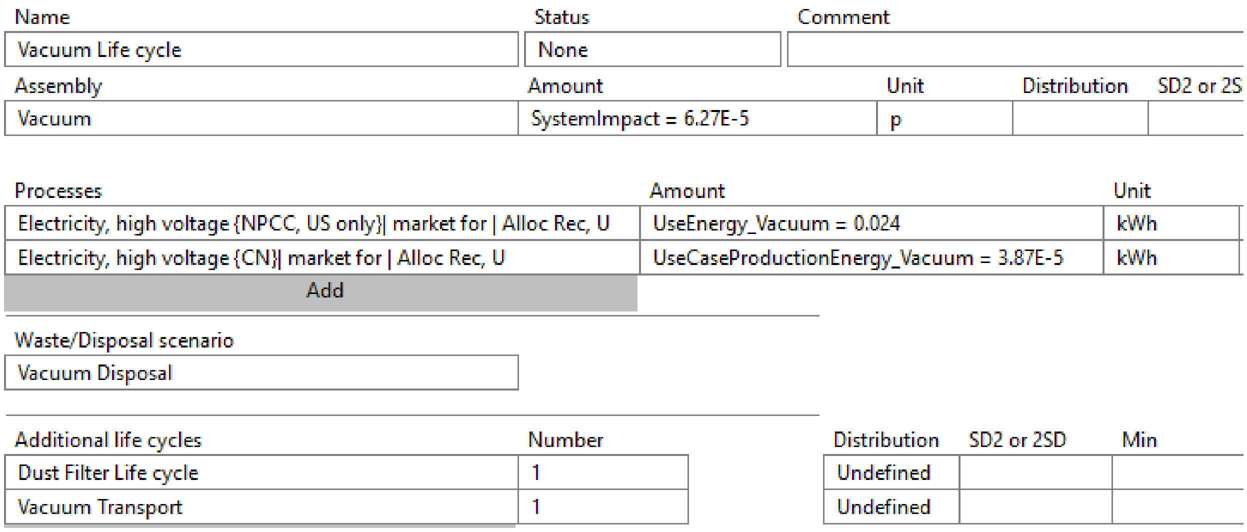

Figure 19: Vacuum System Life Cycle Modeling in SimaPro

Now that the full inventory analysis has been outlined including the product system bill of materials, product system processes, and all associated assumptions the impact assessment can be completed. The impact assessment is the 3rd phase of conducting an LCA when following the ISO 14040 standard and is the phase in which the inventory data is converted into environmental impact estimates. While the SimaPro modeling software carries out the actual impact assessment, consisting of classification, characterization, normalization, and weighting of impacts, the methods and impact categories used in SimaPro will be outlined here before the results are presented.

The intent of this case study is merely to demonstrate the complete usability of the updated methodology proposed in this research; therefore it is not necessary to determine a wide range of impact categories. In order to achieve this purpose this case study assesses the environmental impacts of the Eureka Quick Up 2-in-1 Vacuum System using the IPCC 2013 GWP 100a V1.00 method and the ReCiPe Endpoint H/A V1.12 Single Score method. The IPCC method determines the global warming potential (GWP) of the product system over a 100-year average, which the most widely accepted and commonly used GWP methodology. This IPCC method is chosen to assess the results of this case study because greenhouse gas emission and the global warming potential of products is an area of great interest and commonly a method used when conducting an LCA. The ReCiPe Endpoint Hierarchist (H) method culminates all environmental impacts associated with the system into a three impact categories of ‘human health’, ‘ecosystems’, and ‘resource availability’. The Hierarchist part of this method indicates that the ReCiPe Endpoint results are calculated using industry average assumptions. In addition, the ‘A’ in the ‘H/A’ of this methodology name indicates that a European average weighting set is used, which is the recommended Endpoint method. In general, this Endpoint method is the most commonly used by LCA practitioners because it does not take a too conservative or too liberal calculation approach. In addition, the Endpoint impact categories are commonly used as opposed to the Midpoint impact categories because the Endpoint categories give a simple to interpret overview of the results covering a brought range of categories. The results and interpretation of modeling this case study of the Eureka Quick Up 2-in-1 Vacuum System using SimaPro Version 8 modeling software and the IPCC and ReCiPe impact methods is the final phase of conducting a formal LCA.

6.2.3. Results and Interpretation

6.2.3.1. *SimaPro Results and Interpretation*

The fourth and final phase of an LCA, when following the ISO 14040 standard, is the Interpretation phase, which is when the practitioner conducts a sanity check, assesses the impact assessment for any relevant findings, conducts a sensitivity analysis if deemed relevant, and determines if the goal of the study was ultimately achieved.

As the results of this case study are assessed, a sanity check is conducted by determining if the interpreted results are logical according to the practitioner’s best judgment. A sanity check is not conducted under any scientific method and the outcome is not a guarantee of the results, but rather it determines if the results are plausible. A sanity check on the results of this case study will be conducted concurrently as the interpretation phase is carried out and results are reviewed.

The global warming potential results of the full vacuum life cycle, as seen in Figure 20, shows an overview of the case study results as determined by the IPCC 2013 GWP 100a method. These results are scaled so that they show the relative contribution of each life cycle stage totaling to 100%. The product electricity during use modeled by ‘Electricity, high voltage {NPCC, US Only}’ makes up 79.9% of the total GWP impacts and the Vacuum product system makes up 15.9% of the total GWP impacts. The remaining four life cycle phases modeled in this case study including manufacturing energy, vacuum distribution transportation, dust filter life cycle, vacuum disposal together make up 4.2% of the GWP impacts. Additional case study results in Figure 21 show the damage to human health, ecosystems, and resource availability due to each life cycle phase. These results were determined using the ReCiPe Endpoint Hierarchist method and are expressed in terms of eco-indicator points. The vacuum product system has a total eco-indicator damage of 1.03 milli-points (mPt), the electricity during use has a total eco-indicator damage of 0.95 mPt, and the remaining four life cycle phases modeled have a total eco-indicator damage of 0.045 mPt.

The results shown in Figure 20 and Figure 21 are beneficial for completing an initial sanity check and effectively summarizing the LCA results in terms of life cycle phase. Overall, the relatively high GWP and eco-indicator damage impact due to the vacuum system is logical in this case study because the product has electrical components, which are known to generate higher environmental impacts compared to products without electrical components. In addition, the electricity use results are logical and expected because the use phase electricity is mostly generated from fossil fuels in the region of product use in this case study. Electricity generated from fossil fuels inherently corresponds to a high greenhouse gas or global warming potential impact. Electricity generated from a greater mix of renewable energy sources would have a lower environmental impact than those generated from more non-renewable sources. Due to the greatest GWP impacts and second greatest Endpoint impacts in this case study coming from the use electricity, a sensitivity analysis around the use electricity mix choice is deemed appropriate. This sensitivity analysis, completed in section 6.2.3.2, will demonstrate the extent to which region of product use effects the ultimate life cycle environmental impact results.

Figure 20: Vacuum Life Cycle Global Warming Potential Results

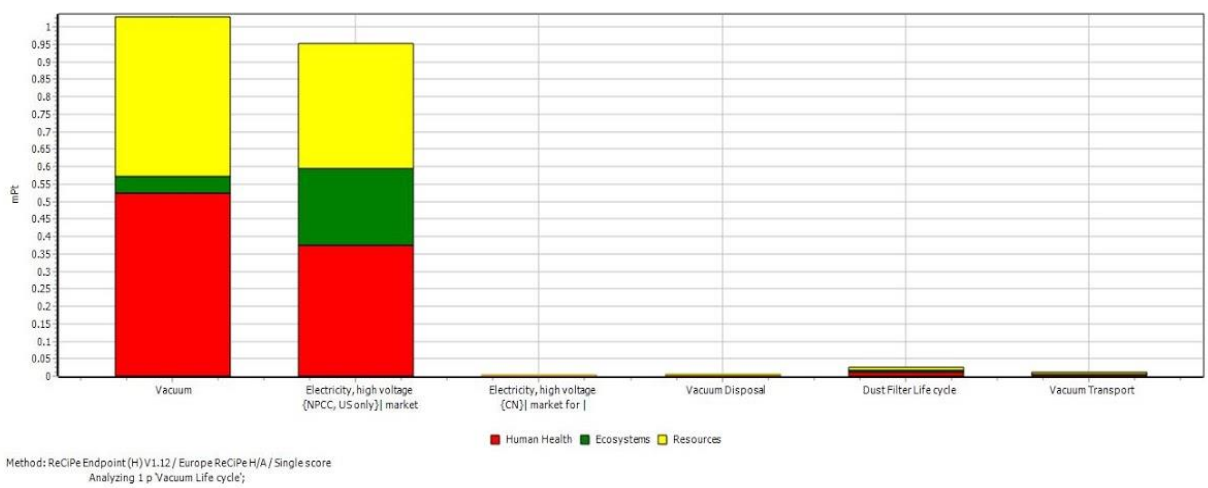

Figure 21: Vacuum Life Cycle ReCiPe Endpoint H/A Results

Overall, this initial overview of results provides valuable insight into the life cycle environmental impacts of the Eureka Quick Up 2-in-1 vacuum system, in addition to passing the initial sanity check. It is a significant finding that these results pass an initial sanity check because this indicates that the proposed methodology has validity and was implemented into this case study in a sound and comprehensible manner.

While Figure 20 and Figure 21 provide a good overview of life cycle results, a deeper dive into some of these results is conducted in order to provide additional environmental impact insights and continue to confirm that the proposed methodology is a valid life cycle goal and scope approach. Figure 22 shows the LCA results of just the physical vacuum product system in network form. The advantage of showing the results of the vacuum system as a network, as seen in Figure 22, is that the practitioner can understand the relative contribution of each subsystem. In this case study it is clear that the power cord subsystem contributes the most environmental impact to the overall system, which is an expected result because it is a fairly long cord and is composed of electrical wiring. As stated previously, it is commonly knowledge that electrical components tend to have a higher environmental impact than non-electrical components. However, it was not fully expected that the power cord would have as high of environmental impacts as the results indicated. It should be noted that the power cord is modeled in this case study using a pre established assembly from Ecoinvent v2.2, which may have resulted in an over estimation of power cord environmental impacts. Since determining the actual life cycle environmental impacts of the Eureka Quick Up 2-in-1 Vacuum is not a main goal of this case study and because the proposed methodology does not affect the impacts associated with the power supply cord, it is not important to further investigate this power cord ambiguity.

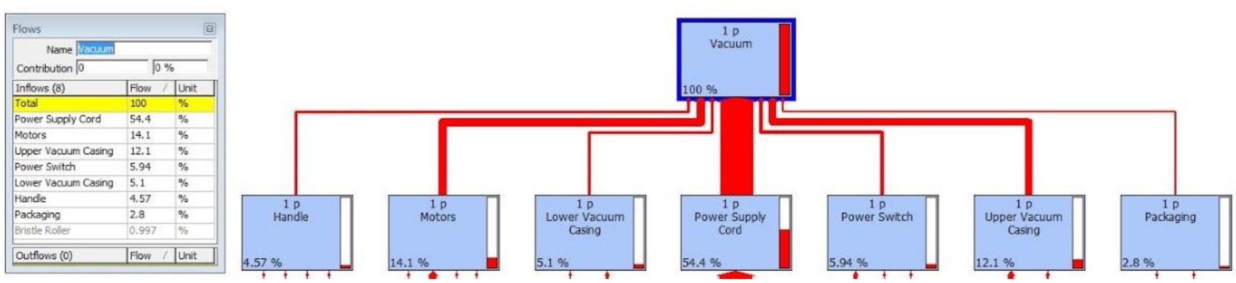

Figure 22: Vacuum Product System ReCiPe Endpoint (H) Results Network

The main goal of this overall case study is to demonstrate that the refined goal and scope methodology proposed in this research is a valid and finalized methodology for completing a full life cycle assessment. By assessing the life cycle environmental impacts of the vacuum system in network form as in Figure 22, these results can continue to validate the soundness of the object-oriented goal and scope methodology used in this case study. Overall, these vacuum system results are logical and expected, therefore continue to pass a sanity check and validate the present goal and scope methodology.

Overall, these results highlight the fact that the use phase is often the most impactful because of the relatively larger environmental impacts associated with electricity use and electricity production. A design team could conclude from these results that design for the environment efforts should focus on replacing the current power supply cord with a less impactful part and reducing the reliance on household electricity during product use. While the design team could do its best to optimize the electricity used by the vacuum, much of this impact is dependent on the end user behavior and regional mix of energy where the end user is located. This conclusion supports the benefit of this methodology, which can be easily updated based on any user behavior and location. In addition, this conclusion reaffirms the need for sensitivity analyses around various use factors and the regional mix of energy used because the final results are most dependent on these model attributes.

The results seen in Figure 20, 21, and 22 reveal the value in conducting sensitivity analyses that specifically test additional use scenario. Sensitivity analyses testing other vacuum use scenarios will contribute additional validity to the present methodology by confirming that the results are in line with expectations and that the initial use scenario results were not an exception. In addition, testing other use scenarios will demonstrate how this methodology lends itself well to easily testing multiple use scenarios on the same system without having to manually recalculate a new functional unit and remodel the entire system.

6.3. Sensitivity Analysis

A sensitivity analysis is conducted in order to determine the source of uncertainty and to what extent each input effects the uncertainty of the output. A sensitivity analysis is completed by recalculating results using alternative assumptions and inputs and evaluating the impact on the initial results. In this case study, a total of four individual sensitivity analyses will be conducted in order to test the effect of changing four different inputs. The intent of the sensitivity analyses in this study is to increase the understanding of relationships between system inputs and results, verify results through a continued sanity check, identify any significant causes of uncertainty, determine any model errors, and identify areas for potential future research.

6.3.1. Regional Use Phase Electricity Sensitivity Analysis

The first sensitivity analysis is to test the effect of regional electricity mix choice on the use phase results. Since the results of this case study indicate that the product use phase electricity contributes the greatest environmental impacts compared to the other life cycle phases, it is important to determine how sensitive these results are to regional electricity mix choice. In the baseline use scenario of this case study, it is assumed that the vacuum end user is located in the north east of the United States and the ecoinvent process ‘Electricity, High Voltage {NPCC, US only}’ was used to model the regional electricity in the baseline use scenario. This sensitivity analysis tests the same baseline use scenario, except with the region of use in Germany and Brazil. Two distinct regions of use are tested in this sensitivity analysis in order to be as thorough as possible when determining the effect of use phase electricity mix input on the results of this case study. The ecoinvent process ‘Electricity, High Voltage {DE}, models the Germany electricity mix and the full life cycle results with an assumed region of use in Germany can be seen in Figure 23. The ecoinvent process ‘Electricity, High Voltage {BR}’, models the Brazil electricity mix and the full life cycle results with an assumed region of use in Brazil can be seen in Figure 24. The IPCC 2013 GWP 100a electricity use results of the baseline use scenario, Germany sensitivity analysis, and Brazil sensitivity analysis are compared in Table 23.

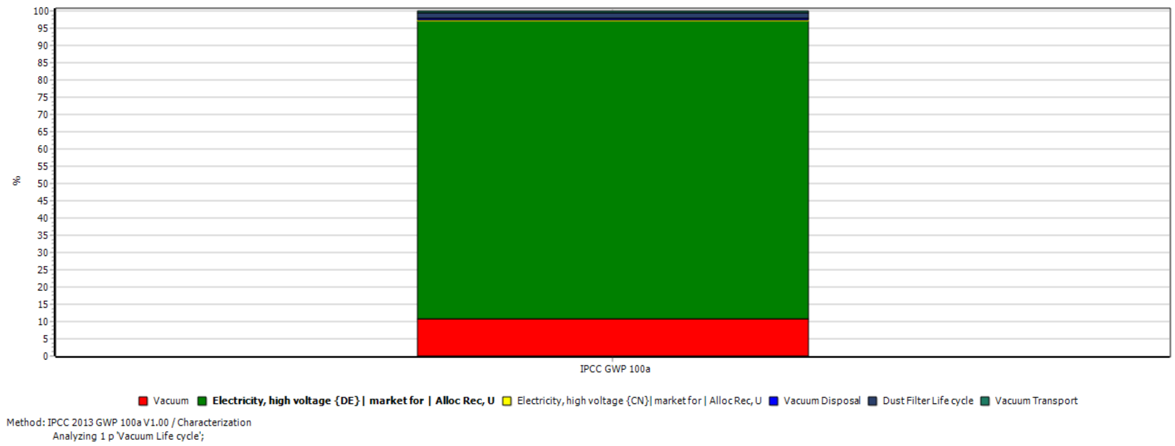

Figure 23: Germany Use Phase Electricity Sensitivity Analysis Results Shown as the Vacuum Life Cycle Global Warming Potential

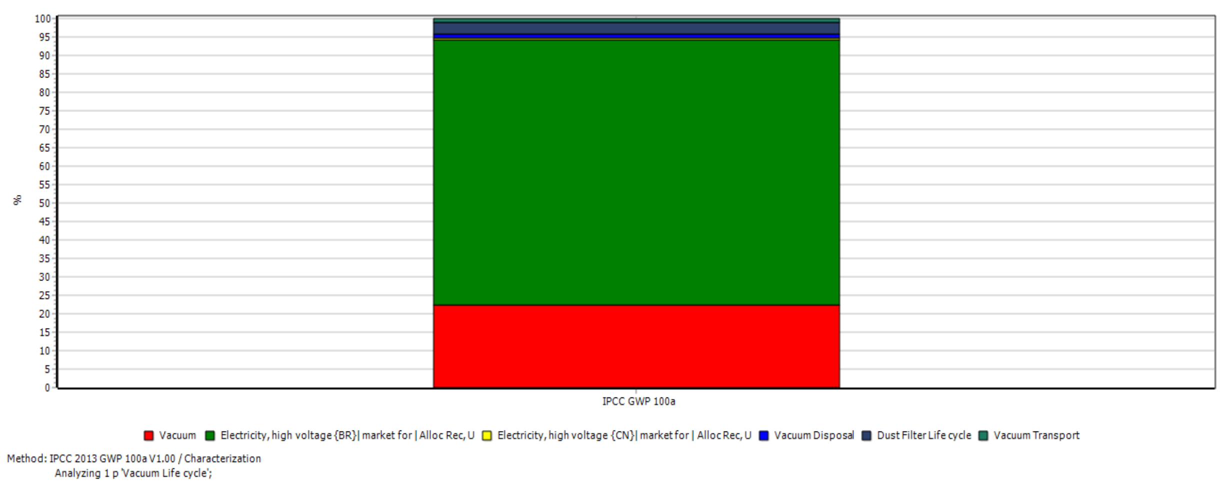

Figure 24: Brazil Use Phase Electricity Sensitivity Analysis Results Shown as the Vacuum Life Cycle Global Warming Potential

Table 23: IPCC GWP Electricity Use Results Comparison

Use Scenario	Ecoinvent Electricity Process Modeled	Total LCA GWP (kg CO_2 eq.)	Electricity GWP (kg CO_2 eq.)	Electricity GWP as a % of Total LCA GWP
Baseline – North East U.S.	Electricity, High Voltage {NPCC, US only}	0.0125	0.00997	79.8%
Germany Sensitivity Analysis	Electricity, High Voltage {DE}	0.0185	0.016	86.5%
Brazil Sensitivity Analysis	Electricity, High Voltage {BR}	0.00886	0.00636	71.8%

Based on the comparative electricity use GWP results shown in Table 23, the baseline results are within an expected range of results. While the range of electricity GWP results in this sensitivity analysis only varies by 0.0476 kg CO_2 eq., this is a significant range because the electricity GWP makes up 71.8 – 86.5 % of the total LCA GWP. The total LCA GWP of the vacuum system used in Brazil is 29% lower than the same product system used in North East U.S. according to this sensitivity analysis. This result is expected as Brazil is one of the world leaders in renewable energy generation according to the Renewables 2018 Global Status Report put together by REN21 (REN21, 2018). By contrast, the total LCA GWP of the vacuum system used in Germany is 48% greater than the same product system used in North East U.S. according to this sensitivity analysis. This result is somewhat unexpected because Germany has made significant investments in renewable energy generation; however Germany's renewables generation is not as great as the U.S. or Brazil. There are other factors besides the amount of renewable energy that go into the GWP of electricity use in this analysis and those factors could be the cause of the significantly large GWP of the Germany electricity use. Renewable energy is used as a sanity check for this sensitivity analysis because the amount of renewable energy inputs in each respective ecoinvent process has a large impact and is the most influential factor on the GWP results.

Overall, this sensitivity analysis confirms that the region of product use significantly impacts the LCA GWP results because regional electricity mixes can vary widely. Furthermore, the results of this sensitivity analysis pass a high-level sanity check, which is an important consideration of the LCA interpretation phase.

6.3.2. Use Scenario Inputs Sensitivity Analyses

Next, a series of 3 additional sensitivity analyses are completed in order to determine the extent to which the time factors, damage multipliers and use scenario parameters each affect the LCA results. In each of these 3 analysis all factors are kept constant except for one that is under analysis. The first of these three analyses uses the same damage multipliers and use scenario parameters as the baseline while the time factors are increased from the baseline. The second analysis uses the same use scenario parameters and time factors as the baseline while the damage multipliers are changed from the baseline. The third analysis uses the same damage multipliers and time factors as the baseline while the use scenario parameters are changed from the baseline.

Table 24 shows the use scenario parameters used in all sensitivity analysis and the baseline scenario. All use scenario parameters are shown in this one table in order to simply compare each scenario to each other and to the baseline. It can easily be seen from Table 24 that the time and efficiency sensitivity analyses use the same use scenario parameters as the baseline, while the use parameter sensitivity analysis tests different use scenario parameters.

Table 24: Quantification of Sensitivity Analysis Use Scenario Parameters

Scaling Parameter	Parameter	Constant Scaling Factor	Baseline Parameter Value	Time Sensitivity Analysis Parameter Value	Damage Multiplier Sensitivity Analysis Parameter Value	Use Parameter Sensitivity Analysis Parameter Value
Reference flow: Kinetic Energy **Unit:** kilowatts						
Power to remove	y_1	1	0.072	0.072	0.072	0.072
Power to move	y_2	1	0	0	0	0
Reference flow: Debris **Unit:** 0.5 mm debris removed						
Large debris	x_1	2	40	40	40	70
Large debris	x_2	0.6	26	26	26	35
Large debris	x_3	0.1	0	0	0	0
Medium debris	x_4	4	85	85	85	70
Medium debris	x_5	1.3	100	100	100	110
Medium debris	x_6	0.2	0	0	0	0
Small debris	x_7	200	300	300	300	325
Small debris	x_8	66	110	110	110	250
Small debris	x_9	4	0	0	0	0

Table 25 shows the quantification of time factors for all of the sensitivity analyses and the baseline scenario. Just as with the comparison of use scenario parameters, all time factors are shown side-by-side in the same table in order to simply compare each scenario to each other and to the baseline. It can easily be seen from Table 25 that the damage multiplier and use parameter sensitivity analyses use the same time factors as the baseline, while the time sensitivity analysis tests different time factors.

Table 25: Quantification of Sensitivity Analysis Time Factors

Time Factor	Parameter	Baseline Parameter Value	Time Sensitivity Analysis Parameter Value	Damage Multiplier Sensitivity Analysis Parameter Value	Use Parameter Sensitivity Analysis Parameter Value
Time in use removing debris	t_1	1200 sec	2300 sec	1200 sec	1200 sec
Time moving device	t_2	0 sec	30 sec	0 sec	0 sec

Lastly, Table 26 shows the quantification of damage multipliers for all of the sensitivity analyses and the baseline scenario. Just as with the comparison of use scenario parameters and time factors, all damage multipliers are shown side-by-side in the same table in order to simply compare each scenario to each other and to the baseline. It can easily be seen from Table 26 that the time and use parameter sensitivity analyses use the same damage multipliers as the baseline, while the damage multiplier sensitivity analysis tests different damage multipliers.

Table 26: Quantification of Sensitivity Analysis Damage Multipliers

Damage Multiplier	Parameter	Baseline Efficiency Value	Time Sensitivity Analysis Parameter Value	Efficiency Sensitivity Analysis Parameter Value	Use Parameter Sensitivity Analysis Parameter Value
Damage of time removing debris	z_1	1.6	1.6	2.1	1.6
Damage of time moving device	z_2	1	1	1.1	1
Area overlap with each device pass	z_3	1.3	1.3	1.2	1.3
Distance between device and surface	z_4	1	1	1	1
Debris collected before debris removal system is replaced	z_5	2	2	2	2
Debris collected before debris removal system is cleaned	z_6	1	1	1.3	1
Total Damage Multiplier (z)	z	4.16	4.16	7.21	4.16

6.3.2.1. *Time Factor Sensitivity Analysis*

The first sensitivity analysis tests the effect of the time factors in this methodology on the results of the case study. Conceptually, the use scenario defined in this analysis reflects a user in a similar use case as the baseline, however the user is moving the vacuum more slowly such that the same amount of debris is picked up with the same vacuum efficiency or damage multiplier, but in a greater amount of time. The use scenario parameters, time factors, and damage multipliers defined in Table 24, 25 and 26 are input into the established SimaPro model and immediate the calculated parameters in Figure 25 are calculated. By simply inputting the new use scenario values, in a matter of seconds, the entire model is updated to reflect the current analysis and results can immediately be seen with no added effort. This simple and nearly immediate updating of the model is a clear advantage of using this use object-oriented methodology compared to the traditional LCA methodology in which a new use scenario needs to be manually calculated and each SimaPro material manually changed. This sensitivity analysis, along with each of the subsequent analyses, helps to successfully achieve a goal of this study which is to demonstrate the ability to simply update a LCA model by using this object-oriented methodology.

Calculated parameters

Name	Expression	Comment
TotalEfficiencyFactor_Vacuum	z1*z2*z3*z4*z5*z6 = 4.16	unitless
UseEnergy_Vacuum	(y1)*(t1/3600) = 0.046	kWh
CDF_debrisremoved_Vacuum	TotalEfficiencyFactor_Vacuum*(x1*2+x2*0.6+x3*0.1+x4*4+x5*1.3+x6*0.2+x7*200+x8*66+x9*4) = 2.82E5	medium debris particles equivalent
SystemImpact	CDF_debrisremoved_Vacuum/LifeSpan_debrisremoved_Vacuum = 6.27E-5	
DustFiltersConsumed	CDF_debrisremoved_Vacuum/LifeSpan_debrisremoved_Dustfilter = 0.000125	
UseCaseWeight_Vacuum	TotalWeight_Vacuum*SystemImpact = 0.000149	kg
UseCaseWeight_DustFilter	TotalWeight_DustFilter*DustFiltersConsumed = 3.39E-5	kg
TransportVacuum_Mfg_Port	UseCaseWeight_Vacuum*Distance_Mfg_Port = 0.00448	kgkm
TransportVacuum_Port_Port	UseCaseWeight_Vacuum*Distance_Port_Port = 1.58	kgkm
TransportVacuum_Port_Distribution	UseCaseWeight_Vacuum*Distance_Port_Distribution = 0.53	kgkm
TransportVacuum_Distribution_Retail	UseCaseWeight_Vacuum*Distance_Distribution_Retail = 0.235	kgkm
TransportDustFilter_Mfg_Distribution	UseCaseWeight_DustFilter*Distance_Port_Distribution = 0.12	kgkm
TransportDustFilter_Distribution_Retail	UseCaseWeight_DustFilter*Distance_Distribution_Retail = 0.0534	kgkm
UseCaseProductionEnergy_Vacuum	0.259*UseCaseWeight_Vacuum = 3.87E-5	kWh (0.259 kWh/kg)
UseCaseProductionEnergy_DustFilter	0.259*UseCaseWeight_DustFilter = 8.77E-6	kWh (0.259 kWh/kg)

Figure 25: Time Factor Sensitivity Analysis Calculated Parameters

The time factors changed in this analysis only effect the 'UseEnergy_Vacuum' calculated parameter, which calculates the amount of energy consumed during the use of the Vacuum. Therefore this analysis isolates the effect of time and therefore energy consumption on the LCA results. The baseline use scenario analysis determined that use phase energy consumption has an IPCC GWP 100a impact of 0.0099 kg CO_2 eq. while the time factor sensitivity analysis use scenario has an impact of 0.0191 kg CO_2 eq.. Figure 26 shows the life cycle GWP results of this time factor sensitivity analysis, in which the use phase energy consumption contributes the largest impact to the overall impacts. Since the time factor itself was increased by 94% from the baseline, it is logical that the GWP impact result also increases by 90% in this sensitivity analysis. This proportional result indicates that the object-oriented methodology was implemented correctly into SimaPro and that the time factor component of this methodology passes a sanity check.

Time factors were always an integral part of LCA methodology. This study merely gave a name to this component and created a more explicit framework step to make sure they are not overlooked. Since this sensitivity analysis results follow the expected outcome, there is confidence that that time factors were developed correctly and seamlessly integrated into the overall object-oriented methodology. In addition, because, as noted, the use phase energy consumption sometimes contributes the largest GWP impact compared to any other life cycle phase, it is a particularly important conclusion that the time factors pass a sanity check.

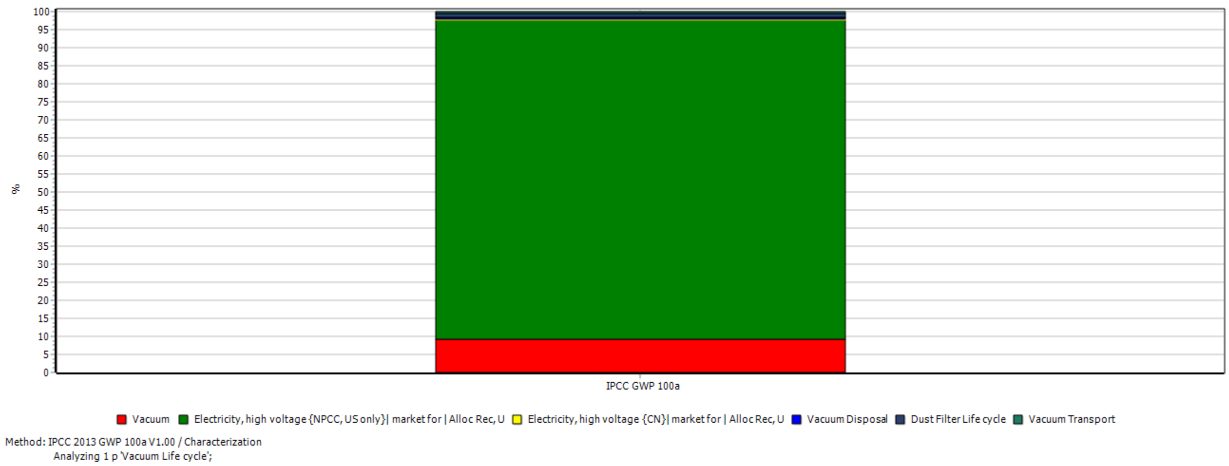

Figure 26: Time Factor Sensitivity Analysis Life Cycle GWP Results

To further test the effect of time factors on the overall life cycle results, the ReCiPe Endpoint H/A method is also implemented to analyze the results. Figure 27 shows the graphical results of the vacuum life cycle ReCiPe Endpoint H/A analysis using the time factor sensitivity analysis use scenario. While the baseline ReCiPe results showed that the vacuum manufacturing life cycle phase contributed the greatest impacts, this use scenario analysis results in the use phase energy consumption phase contributing the greatest impacts compared to any other phase. Just as with the GWP results of this sensitivity analysis, the ReCiPe results indicate a greater use phase energy consumption impact because the increase in time directly increases the energy consumption. Furthermore, this ReCiPe analysis reinforces that life cycle results are highly dependent on the use scenario defined and different conclusions can be drawn based on the defined use scenario. Based on the baseline ReCiPe results the vacuum manufacturing would be the area of highest focus for impact reduction efforts because that is the phase which contributes the greatest eco-indicator point impacts. However, the results of this sensitivity analysis would most likely lead a LCA practitioner to focus impact reduction efforts on the use phase energy consumption. This potential contradiction of results based on use scenario is an interesting finding that warrants greater attention and analysis, but is outside of the scope of this study.

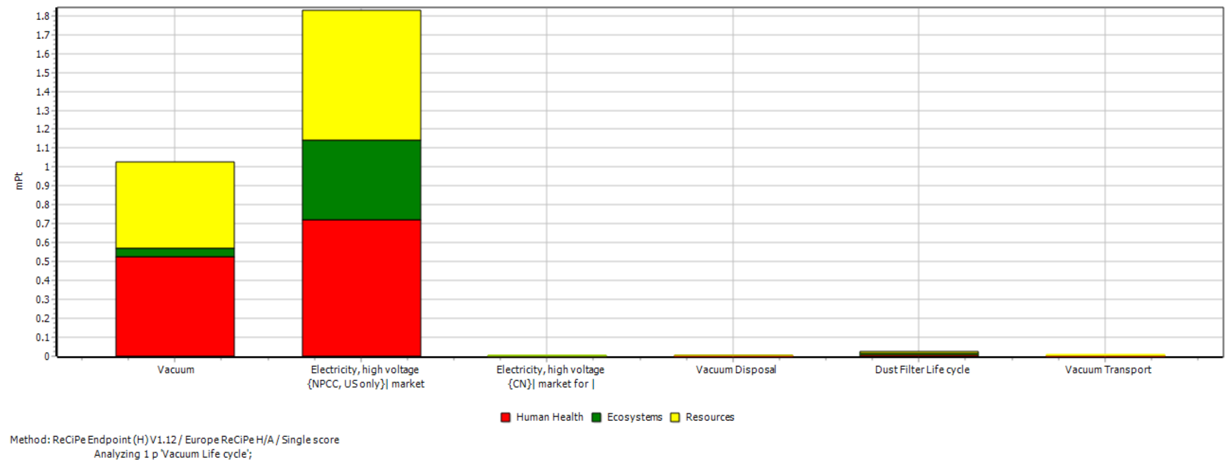

Figure 27: Time Factor Sensitivity Analysis Life Cycle ReCiPe Endpoint H/A Results

6.3.2.2. *Damage Multiplier Sensitivity Analysis*

The second sensitivity analysis tests the effect of the damage multiplier in this methodology on the results of the case study. Conceptually, the use scenario defined in this analysis reflects a user in a similar use case as the baseline, however the user is moving the vacuum generally less efficiently while the same amount of debris is picked up in the same amount of time. In this methodology it is important to remember that time is not a measure of efficiency or damage. The use scenario parameters, time factors, and damage multipliers defined in Table 24, 25 and 26 are input into the established SimaPro model and immediately the calculated parameters in Figure 28 are calculated. Just as with the time factor sensitivity analysis, by simply inputting the new use scenario values, in a matter of seconds, the entire model is updated to reflect the current analysis and results can immediately be seen with no added effort.

Calculated parameters

Name	Expression	Comment
TotalEfficiencyFactor_Vacuum	z1*z2*z3*z4*z5*z6 = 7.21	unitless
UseEnergy_Vacuum	(y1)*(t1/3600) = 0.024	kWh
CDF_debrisremoved_Vacuum	TotalEfficiencyFactor_Vacuum*(x1*2+x2*0.6+x3*0.1+x4*4+x5*1.3+x6*0.2+x7*200+x8*66+x9*4) = 4.89E5	medium debris particles equivalent
SystemImpact	CDF_debrisremoved_Vacuum/LifeSpan_debrisremoved_Vacuum = 0.000109	
DustFiltersConsumed	CDF_debrisremoved_Vacuum/LifeSpan_debrisremoved_Dustfilter = 0.000217	
UseCaseWeight_Vacuum	TotalWeight_Vacuum*SystemImpact = 0.000259	kg
UseCaseWeight_DustFilter	TotalWeight_DustFilter*DustFiltersConsumed = 5.87E-5	kg
TransportVacuum_Mfg_Port	UseCaseWeight_Vacuum*Distance_Mfg_Port = 0.00776	kgkm
TransportVacuum_Port_Port	UseCaseWeight_Vacuum*Distance_Port_Port = 2.74	kgkm
TransportVacuum_Port_Distribution	UseCaseWeight_Vacuum*Distance_Port_Distribution = 0.918	kgkm
TransportVacuum_Distribution_Retail	UseCaseWeight_Vacuum*Distance_Distribution_Retail = 0.408	kgkm
TransportDustFilter_Mfg_Distribution	UseCaseWeight_DustFilter*Distance_Port_Distribution = 0.208	kgkm
TransportDustFilter_Distribution_Retail	UseCaseWeight_DustFilter*Distance_Distribution_Retail = 0.0925	kgkm
UseCaseProductionEnergy_Vacuum	0.259*UseCaseWeight_Vacuum = 6.7E-5	kWh (0.259 kWh/kg)
UseCaseProductionEnergy_DustFilter	0.259*UseCaseWeight_DustFilter = 1.52E-5	kWh (0.259 kWh/kg)

Figure 28: Damage Multiplier Sensitivity Analysis Calculated Parameters

The damage multipliers are inputs to the calculated parameter of 'TotalDamageMultiplier_Vacuum', which determines the total damage multiplier for the given use scenario. This total damage multiplier value is used in the vacuum Cumulative Damage Function, listed in Figure 28 as 'CDF_debrisremoved_Vacuum'. As a reminder, the CDF determines what portion of the vacuum's useful life should be modeled to reflect the given use scenario. This means that the damage multipliers only contribute to calculated parameters that effect the physical vacuum product system.

The results of this sensitivity analysis expect to differ from the baseline results in the vacuum manufacture, disposal, dust filter life cycle, and vacuum transportation phases, which includes all phases except the use phase energy consumption. Figure 29 and Figure 30 show the results of this sensitivity analysis using the IPCC GWP 100a and ReCiPe Endpoint H/A methods, respectively. The results shown in these figures align with the expected results in that the impacts from all life cycle phases, except the use phase energy consumption, increase. The total damage multiplier was increased by 73% and the vacuum impact results increased by 63%. This proportional result indicates that the object-oriented methodology was implemented correctly into SimaPro and that the damage multiplier component of this methodology passes a sanity check. Since the actual results match the trend of expected results it is safe to conclude that this sensitivity analysis passes a sanity check. Once again, since the damage multipliers were a newly defined component in this study it is important to highlight that this analysis passes a sanity check, which implies that the factors were developed appropriately and seamlessly integrate into the overall object-oriented methodology.

An interesting point to note about the eco-indicator point results shown in Figure 30 is that, since the vacuum manufacturing impacts increased and the energy consumption impacts remained the same, compared to the baseline, the relative contribution of manufacturing impacts is even greater in this analysis. This means that an LCA practitioner would easily conclude from these results that design for the environment efforts should be focused on the vacuum system itself rather than the energy consumption. This would be an even easier conclusion to draw from these results compared to the baseline results because the vacuum system impacts are even greater in this analysis. This observation of differing conclusions from different use scenarios is the same observation pointed out in the time factor sensitivity analysis. Once again, this potential contradiction of results based on use scenario is an interesting finding that warrants greater attention and analysis, but is outside of the scope of this study.

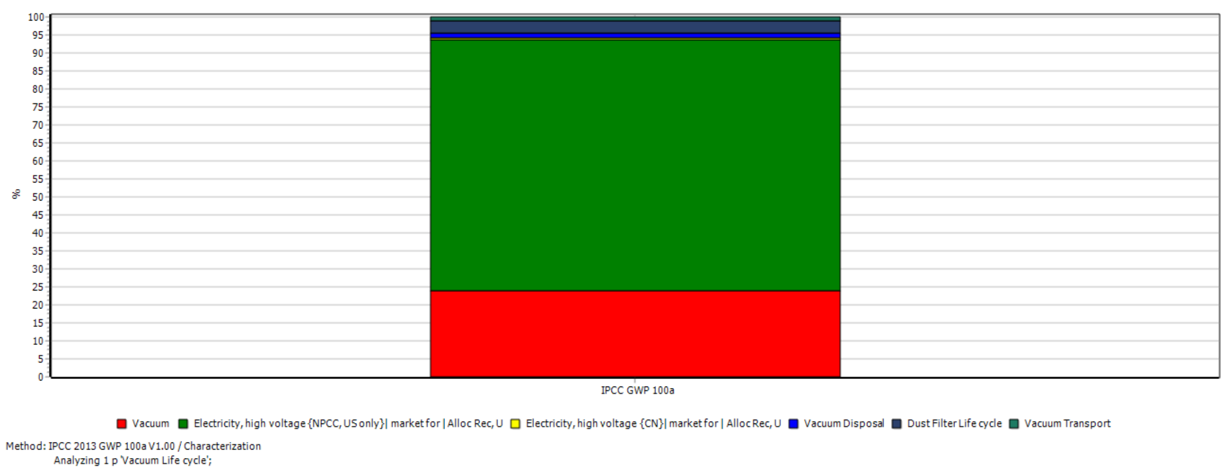

Figure 29: Damage Multiplier Sensitivity Analysis IPCC GWP 100a Results

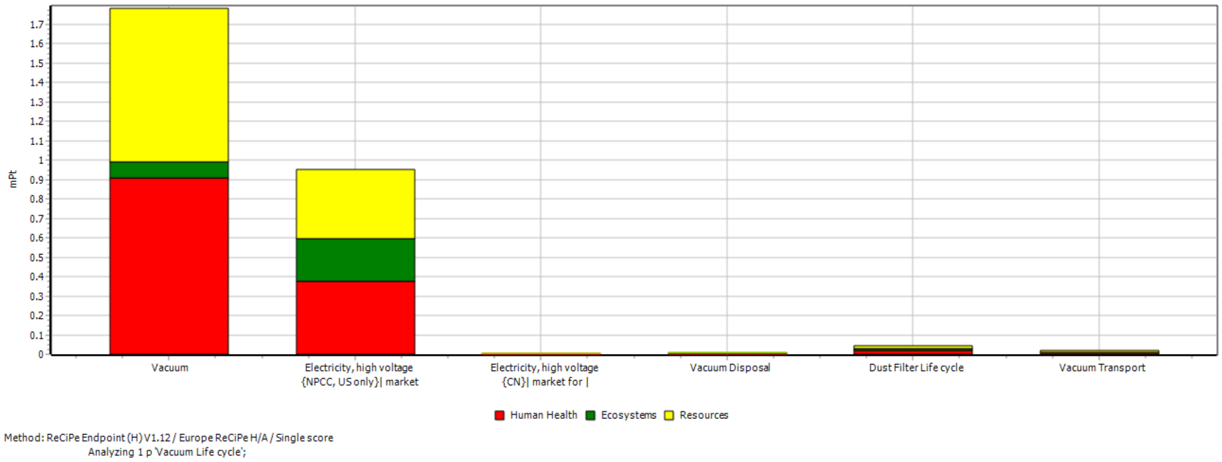

Figure 30: Damage Multiplier Sensitivity Analysis Life Cycle ReCiPe Endpoint H/A Results

6.3.2.3. *Use Scenario Parameters Sensitivity Analysis*

The final sensitivity analysis tests the effect of the use scenario parameters in this methodology on the results of the case study. Conceptually, the use scenario defined in this analysis reflects a user in a similar use case as the baseline, however the user is picking up more debris while moving the vacuum equally as efficiently in the same amount of time. The use scenario parameters, time factors, and damage multipliers defined in Table 24, 25 and 26 are input into the established SimaPro model and immediately the calculated parameters in Figure 31 are calculated. Just as with the previous two sensitivity analyses, by simply inputting the new use scenario values, in a matter of seconds, the entire model is updated to reflect the current analysis and results can immediately be seen with no added effort.

Calculated parameters

Name	Expression	Comment
TotalEfficiencyFactor_Vacuum	z1*z2*z3*z4*z5*z6 = 4.16	unitless
UseEnergy_Vacuum	(y1)*(t1/3600) = 0.024	kWh
CDF_debrisremoved_Vacuum	TotalEfficiencyFactor_Vacuum*(x1*2+x2*0.6+x3*0.1+x4*4+x5*1.3+x6*0.2+x7*200+x8*66+x9*4) = 3.41E5	medium debris particles equivalent
SystemImpact	CDF_debrisremoved_Vacuum/LifeSpan_debrisremoved_Vacuum = 7.59E-5	
DustFiltersConsumed	CDF_debrisremoved_Vacuum/LifeSpan_debrisremoved_Dustfilter = 0.000152	
UseCaseWeight_Vacuum	TotalWeight_Vacuum*SystemImpact = 0.000181	kg
UseCaseWeight_DustFilter	TotalWeight_DustFilter*DustFiltersConsumed = 4.1E-5	kg
TransportVacuum_Mfg_Port	UseCaseWeight_Vacuum*Distance_Mfg_Port = 0.00542	kgkm
TransportVacuum_Port_Port	UseCaseWeight_Vacuum*Distance_Port_Port = 1.91	kgkm
TransportVacuum_Port_Distribution	UseCaseWeight_Vacuum*Distance_Port_Distribution = 0.641	kgkm
TransportVacuum_Distribution_Retail	UseCaseWeight_Vacuum*Distance_Distribution_Retail = 0.285	kgkm
TransportDustFilter_Mfg_Distribution	UseCaseWeight_DustFilter*Distance_Port_Distribution = 0.145	kgkm
TransportDustFilter_Distribution_Retail	UseCaseWeight_DustFilter*Distance_Distribution_Retail = 0.0646	kgkm
UseCaseProductionEnergy_Vacuum	0.259*UseCaseWeight_Vacuum = 4.68E-5	kWh (0.259 kWh/kg)
UseCaseProductionEnergy_DustFilter	0.259*UseCaseWeight_DustFilter = 1.06E-5	kWh (0.259 kWh/kg)

Figure 31: Use Scenario Parameters Sensitivity Analysis Calculated Parameters

The use scenario parameters are the main inputs and driving factors to the Cumulative Damage Function, which is represented as a calculated parameter in Figure 31 as ‘CDF_debrisremoved_Vacuum’. Since the CDF determines what portion of the vacuum’s useful life should be modeled to reflect the given use scenario, the use scenario parameters only contribute to the results of the physical vacuum product system.

Just as with the damage multiplier sensitivity analysis, the results of this use scenario parameters sensitivity analysis expect to see an increase in environmental impacts of all life cycle phases except the use phase energy consumption. The IPCC GWP 100a impacts and ReCiPe Endpoint H/A results of this sensitivity analysis use scenario can be seen in Figure 32 and Figure 33, respectively.

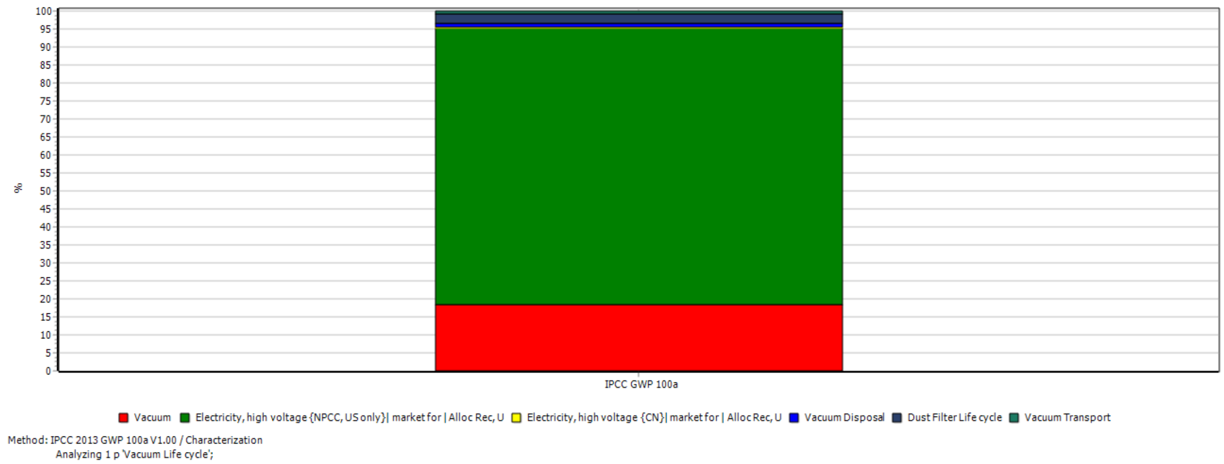

Figure 32: Use Scenario Parameter Sensitivity Analysis IPCC GWP 100a Results

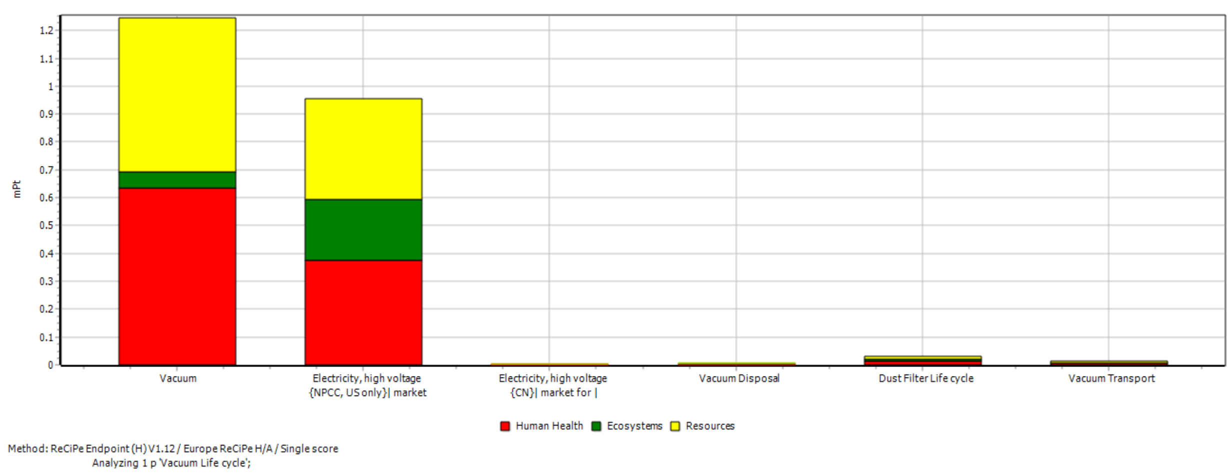

Figure 33: Use Scenario Parameter Sensitivity Analysis ReCiPe Endpoint H/A Results

The GPW and eco-indicator point results of this sensitivity analysis show that the total impact of the vacuum system increased by 0.0005 kg CO2 eq. and 0.22 mPt compared to the baseline results. The total use scenario parameters were increased by 21% and the vacuum impact results increased by 18%. This proportional result indicates that the object-oriented methodology was implemented correctly into SimaPro and that the damage multiplier component of this methodology passes a sanity check. This increase in environmental impacts from the baseline is an expected result just as with the damage multiplier sensitivity analysis, which also implies that this sensitivity analysis passes a sanity check.

Each of the sensitivity analyses discussed in section *6.2.4 Sensitivity Analysis* add a great deal of value and insight to the results of this case study and to the research study as a whole. In addition, because each of the sensitivity analyses passes a sanity check there is greater confidence that the proposed methodology is accurate, well developed, and has the potential to revolutionize how product system LCAs are implemented.

7. Conclusion and Future Research

7.1. Case Study Conclusions and Significance

This study proposed a methodology that can enable LCA practitioners to overcome the shortcomings of current LCA methodology and subsequently have more confidence in the accuracy of results. The proposed methodology is an extension of the work of Fumagalli (2012) and Esterman et al. (2012). While the proposed methodology was encouraging in that it addressed issues with functional unit definition, boundary selection, special variation, local environmental uniqueness, and data availability and quality, it did not develop a complete robust framework for widespread application. In this thesis, a methodology was proposed and tested to address some of the limitations of this previous work, including integrating functional decomposition into the process and systematic identification of use and scaling parameters.

The research in this thesis improved the framework that existed by identifying shortcomings, addressing these shortcomings and validating the proposed improvements through a case study. Four areas were identified as shortcomings, which established the primary areas of improvement including:

1. Further refinement of the 'Allocation' function and process
2. Systematic definition of use parameters and scaling parameters
3. Identification of product system damage multipliers
4. Definition of an explicit methodology for defining use phase energy consumption

Each of these areas of improvement were studied and a clear set of steps were developed and integrated into the full methodology. Initial literature research helped to improve these areas, while the implementation enabled a more structured and thorough definition of these improvement areas. The fully developed and improved methodology was implemented on a case study of the Eureka 2-in-1 Quick Up Vacuum system in order to meet the study goal of demonstrating the practical implementation of the full methodology. The case study was implemented using SimaPro Version 8 modeling software and the IPCC and ReCiPe impact methods.

The LCA results of this case study show that the product electricity during use makes up 79.9% of the total GWP impacts and the Vacuum product system makes up 15.9% of the total

GWP impacts. The remaining four life cycle phases modeled in this case study including manufacturing energy, vacuum distribution transportation, dust filter life cycle, vacuum disposal together make up 4.2% of the GWP impacts. In addition, using the ReCiPe methodology, the vacuum product system has a total eco-indicator damage of 1.03 milli-points (mPt), the electricity during use has a total eco-indicator damage of 0.95 mPt, and the remaining four life cycle phases modeled have a total eco-indicator damage of 0.045 mPt. Overall, the relatively high GWP and eco-indicator damage impact due to the vacuum system and the electricity use are logical and expected. The lowest GWP and eco-indicator impact in the case study is associated with the manufacturing energy, which is also a logical. These GWP and eco-indicator results were beneficial for completing an initial sanity check and effectively summarizing the LCA results in terms of life cycle phase. However, it is important to reiterate that every use scenario modeled will result in a different system impact, a different percentage of the product system modeled, and therefore different results. The overall intent of this case study, is to establish that the use scenarios modeled generate meaningful results, which can increase confidence in the proposed methodology.

All results analyzed in the case study pass an initial sanity check, which indicates that the proposed methodology has validity and was implemented into this case study in a sound and comprehensible manner. In order to further validate the results and conclusions of this study a sensitivity analysis is conducted in order to determine the source of uncertainty and to what extent each input effects the uncertainty of the output. In this study, a total of four individual sensitivity analyses were conducted in order to test the effect of changing four different inputs. The first sensitivity analysis tested the effect of regional electricity mix choice on the use phase results. In the baseline use scenario of this case study, it is assumed that the vacuum end user is located in the north east of the United States and the ecoinvent process ‘Electricity, High Voltage {NPCC, US only}’ was used to model the regional electricity in the baseline use scenario. This sensitivity analysis tested the same baseline use scenario, except with the region of use in Germany and Brazil. Based on the comparative electricity use GWP results, the baseline results are within an expected range of results.

Next, a series of 3 additional sensitivity analyses were completed in order to determine the extent to which the time factors, damage multipliers and use scenario parameters each affect the LCA results. The first of these three analyses uses the same damage multipliers and use scenario parameters as the baseline while the time factors are increased from the baseline. The second analysis uses the same use scenario parameters and time factors as the baseline while the damage multiplier are changed from the baseline. The third analysis uses the same damage multipliers and time factors as the baseline while the use scenario parameters are changed from the baseline. Each of these sensitivity analyses were carried out by updating the baseline model in SimaPro and assess the GWP and ReCiPe eco-indicator results for validity. Each of the sensitivity analysis demonstrated that the results changed proportionally to the amount each factor was changed, which is expected due to the linear quantitative relationship each factor has in the Cumulative Damage Function.

Each of the sensitivity analyses passed a comprehensive assessment and sanity check, therefore supporting greater confidence that the proposed methodology is accurate, well developed, and has the potential to improve how product system LCAs are implemented. This summarizes the LCA results of the case study implementation, which is critical in demonstrating the feasible implementation of this methodology.

Through the process of developing this proposed methodology and case study implementation, important finding were made on the improvements to the allocation function, establishing a methodology step for energy consumption, effectiveness of defining use and scaling parameters, and establishment of damage multipliers. The improvements to the allocation function do not directly affect the quantitative results, but they helped provide clarity to terminology. Motivation for this study was that lack of detailed LCA methodology is a contributing factor to inconsistent or varying results from practitioner to practitioner. The improvements to the allocation function and creating an explicit step for energy quantification help to provide detail in the methodology. With more detail and structure, the intent is that there will be less variability or room for error when more than one practitioner conducts an LCA on the same product system.

The goal of creating a methodology that would limit the variability of results between practitioners is critical to the success of the object-oriented framework. When implementing the case study, the process of defining product use parameters shed light on how the possible variability in generating the system functional decomposition could affect the consistency of results. A side-by-side comparison of three iterations of functional decomposition showed that differences in functional decomposition do not affect the definition of product use parameters in this methodology. While the functional decompositions in the comparison did vary in terminology and structure, the translation to use parameters was consistent overall. This supports the conclusion that this object-oriented approach to defining use parameters helps remove practitioner variability.

The exercise of comparing functional decomposition iterations to determine the effect on the use parameter definition was important because overall, the use and scaling parameters and use scenario inputs are the main inputs and driving factors to the Cumulative Damage Function. The methodology developed in this study to systematically define all use parameters integrates seamlessly in the object-oriented framework. This is important for the ease of use by practitioners. If a methodology was developed, that was overly complex or outside the realm of knowledge for a typical LCA practitioner or design for the environment teams, the method would not be practically feasible for widespread acceptance. While there will always be some subjectivity to LCA goal and scope definition due to varying knowledge, limited data availability and human error, the methodology developed in this study significantly improves upon the lack of guidance that existed previously. The case study helps to demonstrate that the proposed method for defining use and scaling parameters is effective and exhaustive in capturing the complete use phase of the product system. The only concern is that this approach could potentially overestimate impacts by double counting if use parameters overlap or are depended on one another. This concern is mitigated if all practitioners follow the same methodology steps and therefore results are comparable, even if slightly over estimated. Once again, there is a clear advantage of having detailed methodology steps for goal and scope phase definition.

The final area of improvement that this research addresses is the establishment of damage multiplier. The total damage multiplier is an input to the cumulative damage function and is a newly developed input that was not identified in the previous Dynamic LCA Framework or other works developing the Object-Oriented Framework. Damage multipliers were developed from the basis of Telenko & Sepersad’s (2012) framework of identifying human use factors. Damage multipliers account for the user variability, which is critical to modeling an accurate and realistic LCA use phase. The impact associated with user variability was never truly captured previously so this addition to LCA methodology could have a significant impact on creating more accurate results. In addition, the damage multiplier sensitive analysis helps provide more confidence in the implementation of damage multipliers. However, it is also recognized that efficiency or damage is difficult to reliably quantify without time-consuming situational testing. In this case study application, reasonable estimates were used to quantify the damage multipliers and this research did not attempt to conduct situational testing in order to conclusively define efficiency or damage. This study takes the first step in proving the feasible implementation of damage multipliers, while future research should be conducted to further the reliable quantification. The discovery of damage multipliers provides the opportunities for more realistic modeling of product system impacts during its use phase. This improvement can ultimately help drive better design decisions because design teams will have a complete assessment of customer impacts.

In conclusion, this study demonstrates that the refined goal and scope methodology proposed in this research creates a more comprehensive step-by-step framework for quantifying the consumed life a product system. Furthermore, this methodology can reduce variability when comparing LCAs of the same product, enables a practitioner to easily update the model and the method can be seamlessly integrated with product development as an effective design for the environment tool.

7.2. Future Work

As the present research was developed and implemented, future work was identified as proposed suggestions for overcoming potential limitations. Specifically there are three aspects identified that need added guidance as part of this goal and scope methodology. First, the distinction between applying this methodology to an LCA study versus product development. In both applications, capturing a realistic end-user scenario is vital to the results. However, for an LCA study a practitioner can apply the methodology in its current state, while for product development this methodology must be integrated into a design tool or process. This area needs future work because one of the goals and intended applications of the Object-Oriented framework is to create a modular tool for product development. Gadre (2016) demonstrates the modular ability of the Object-Oriented framework to help simplify product development, but does not test its integration into current design tools and processes used by industry.

The second area for future work is to develop a guideline for determining what use scenario is appropriate for analysis in certain applications. As is evident from the research in this Thesis, use scenario and user behavior results can lead to a wide range of results. A wide range of results could cause non-comparable results between industry practitioners and/or identifying varying areas for design improvement. Future research can be focused on how to determine an average use scenario or guidelines on choosing a use scenario to analyze based on the application and industry.

The third area for future work is to conduct a case study using situational and product testing to quantify use parameters and damage multipliers. The work to develop the Dynamic and Object-Oriented methodology use best estimates for quantifying use parameters and damage multipliers. Implementing the refined Object-Oriented methodology on a case study that focuses on using situational and product testing to quantify parameters and factors would further validate the use of this methodology for LCA practitioners and design for environment teams.

8. References

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9. Appendix A

Refinement of Case Study Product System Choice by Characteristic

Criteria	Availability of different technologies providing the same function	Multiple common use scenarios	Reasonable complexity of system	Single function product system
Product / **Target**	≥2 other technologies	≥2 other use scenarios defined	Sufficient # of moving parts	Product only has 1 main function
Printer	Y	Y	Y	Y
Stapler	N	Y	N	Y
Copy Machine	Y	Y	Y	N
Paper Shredder	Y	Y	Y	Y
Humidifier	N	Y	N	Y
Tooth brush	Y	Y	N	Y
Rice Cooker	Y	Y	N	Y
Lawn Mower	Y	Y	Y	Y
Blender	Y	Y	Y	N
Microwave	Y	Y	N	Y
Fan	Y	Y	N	Y
Wine Opener	Y	Y	N	N
Can Opener	Y	Y	N	Y
Coffee Maker	Y	Y	Y	Y
Refrigerator	Y	Y	N	Y
Dishwasher	Y	Y	Y	N
Iron	N	Y	N	Y
Jig-Saw	Y	Y	Y	Y
Sink Waste Disposal	N	Y	N	Y
Hair Straightener	Y	Y	N	N
Clothes Dryer	Y	Y	N	Y
Radio	Y	Y	N	Y
Sewing Machine	N	Y	Y	Y
Vacuum Cleaner	Y	Y	Y	Y
Air Conditioner	N	Y	Y	Y
Hair Dryer	Y	Y	N	Y
TV	Y	Y	N	N
Toaster	Y	Y	Y	Y
Computer	N	Y	N	N
Dehumidifier	N	Y	N	Y
Clock	Y	N	N	Y
Juicer	Y	Y	Y	Y
Clothes Washer	N	Y	Y	Y